

Potential Impacts of Aerosols on Precipitation and Stream Flow in California

An aerial photograph of a mountainous landscape, likely the Sierra Nevada in California. The foreground shows a dense forest of green trees. Above the forest, the sky is filled with large, billowing white and grey clouds. The mountains in the background are partially obscured by these clouds, creating a dramatic and misty atmosphere.

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The Hebrew University of Jerusalem, Israel

Orographic clouds snowing over Yosemite.

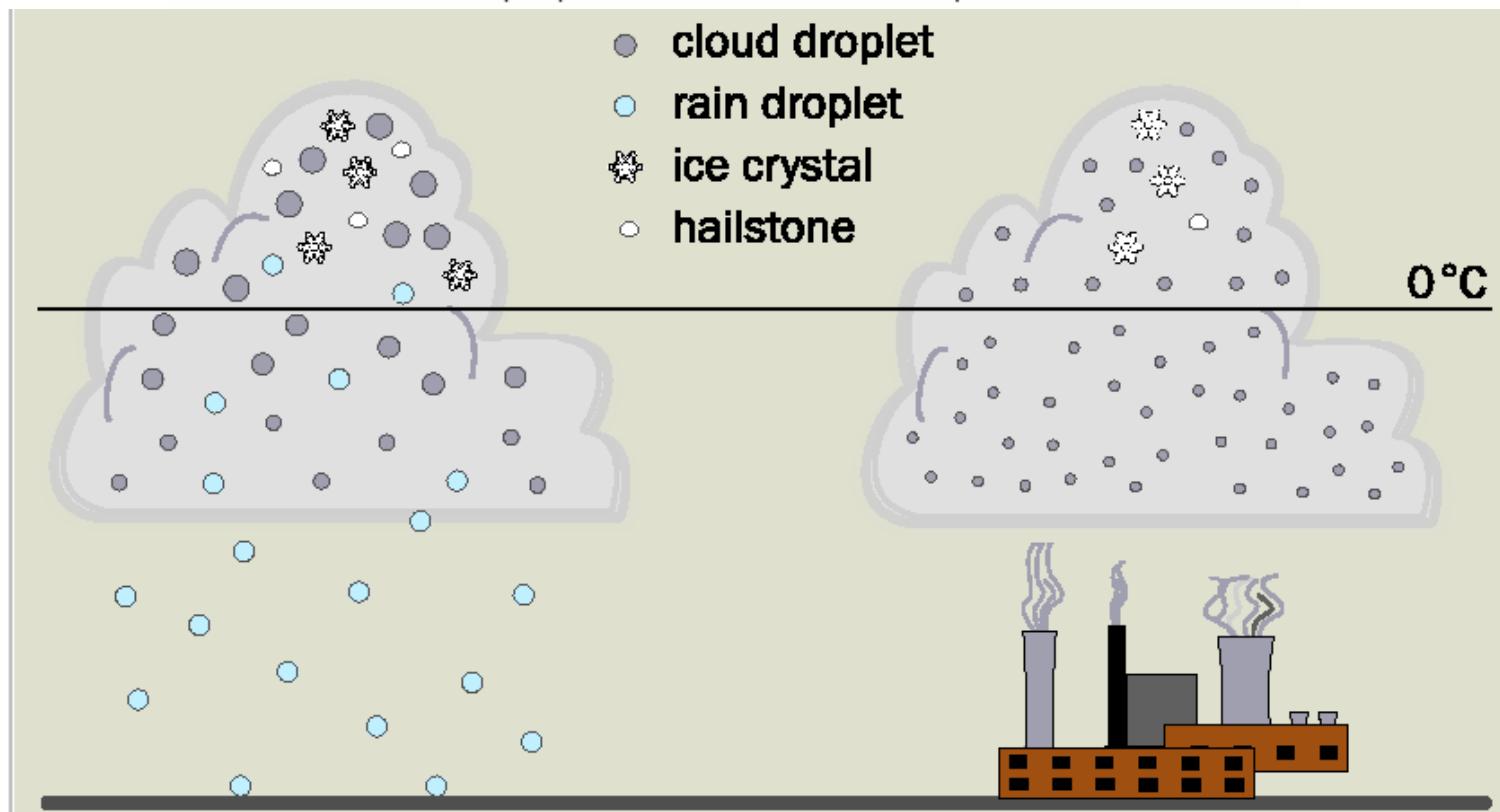
2004 02 28 17:08 GMT.

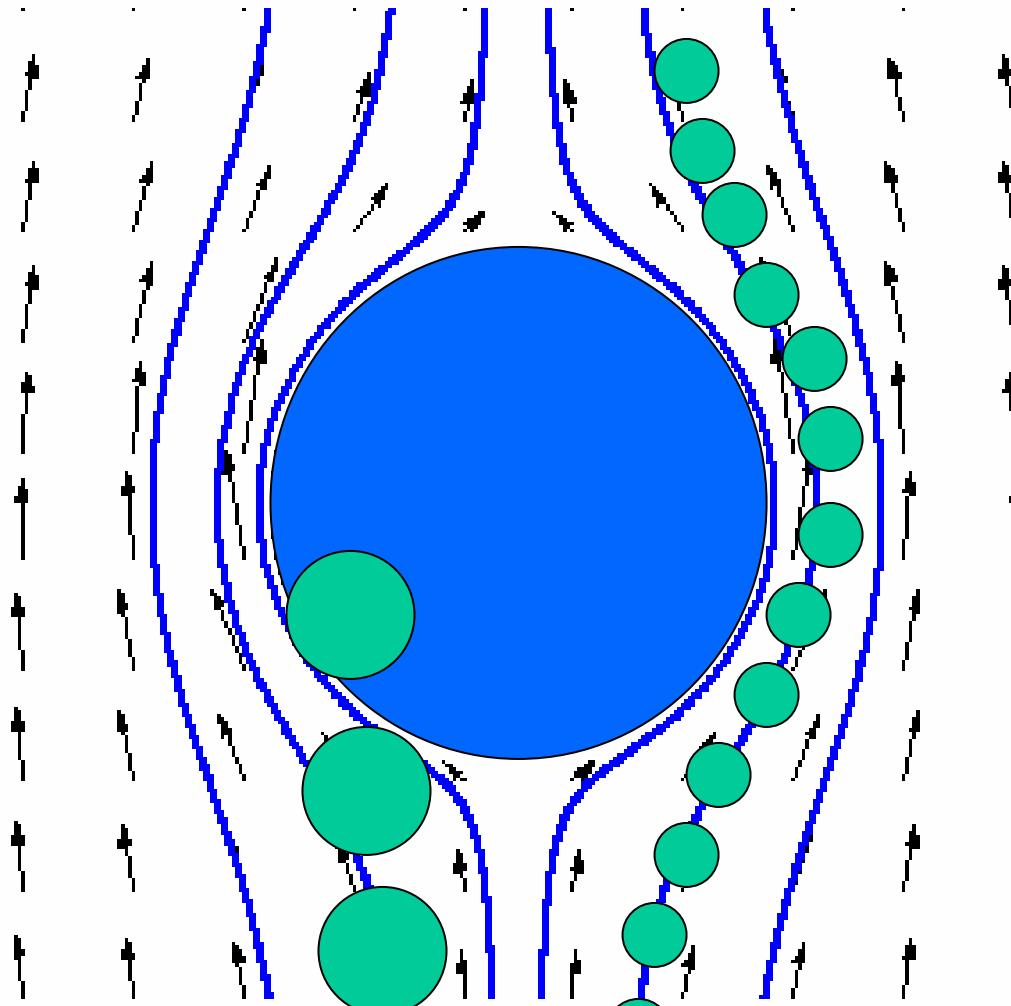
Photo: D. Rosenfeld

Suppression of Rain and Snow by Urban and Industrial Air Pollution

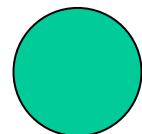
Daniel Rosenfeld

Direct evidence demonstrates that urban and industrial air pollution can completely shut off precipitation from clouds that have temperatures at their tops of about -10°C over large areas. Satellite data reveal plumes of reduced cloud particle size and suppressed precipitation originating from major urban areas and from industrial facilities such as power plants. Measurements obtained by the Tropical Rainfall Measuring Mission satellite reveal that both cloud droplet coalescence and ice precipitation formation are inhibited in polluted clouds.

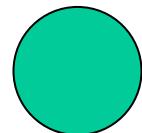




Large droplets collide
with the falling drop



- Small droplets follow the airflow streamlines and bypass the falling drop
- Large droplets collide with the falling drop



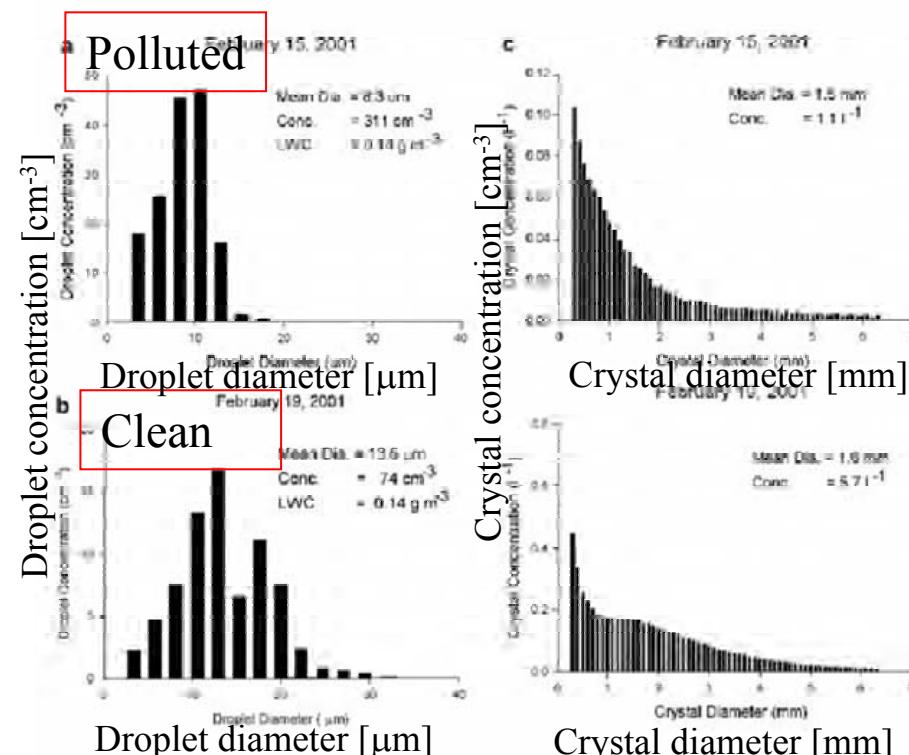


Figure 4. Cloud droplet and snow size spectra for the sampling periods on Feb. 15 and 19, 2001.

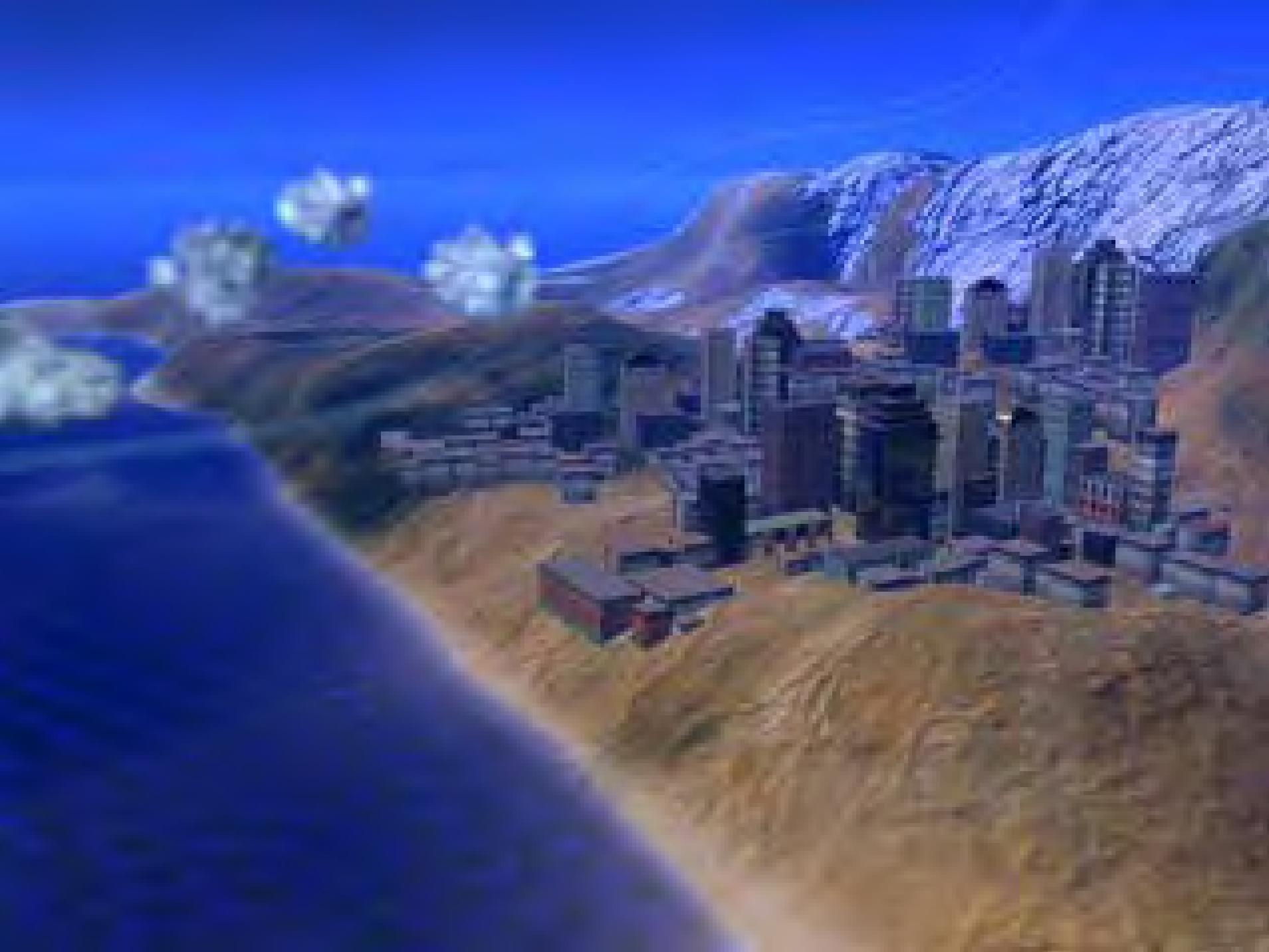
The difference between the cloud clear air equivalent anthropogenic aerosol sulfate concentrations on the two days is nearly an order of magnitude, but in absolute terms it is **only 1 $\mu\text{g m}^{-3}$. Astonishingly, this small amount of aerosol can reduce the snowfall rate up to 50%.**

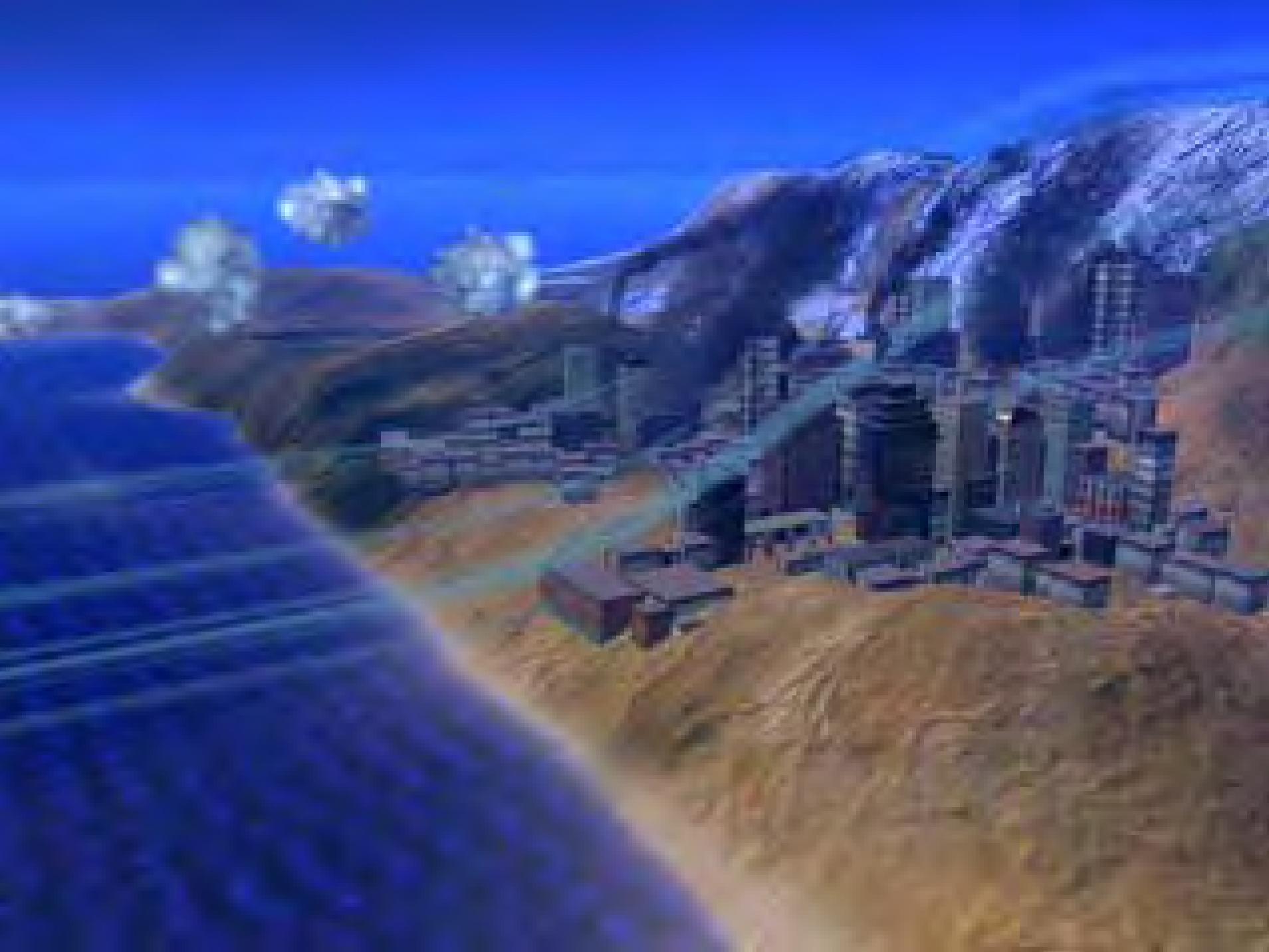
Evidence is presented to demonstrate the possible magnitude of the secondary indirect aerosol effect on precipitation rates from cold mixed-phase clouds in mountainous regions where a seeder-feeder cloud couplet is present. Changes as small as 1 $\mu\text{g m}^{-3}$ in CCN aerosol concentration can cause significant changes in cloud properties and precipitation efficiencies. (Quoted from Borys et al., GRL 2003).

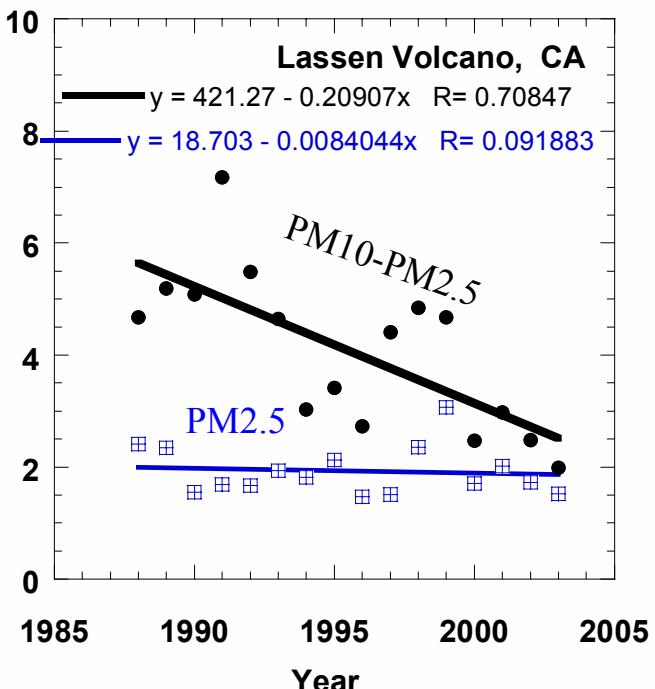
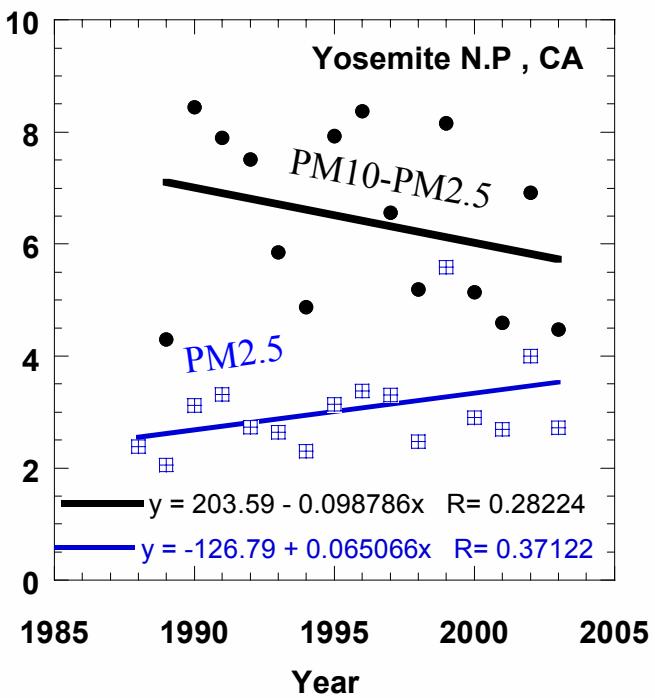
Table 1. Chemical and Physical Properties of Cloud Droplets and Snow During Two Precipitation Events

February	15	19
Major Habit	Planar Dendrite	Planar Dendrite
Rime Category	Unrimed (0.5)	Moderate (2.0)
Rime Mass Frac.	5%	51%
SPL Precip. Rate	0.02 mm hr^{-1}	0.38 mm hr^{-1}
ISS Precip. Rate	0 to 0.1 mm hr^{-1}	1.1 mm hr^{-1}
SPL Temperature	-13°C	-4°C
Snow $\delta^{18}\text{O}$	-22.1	-16.5
Cloud $\delta^{18}\text{O}$	-21.1	-16.2
$\delta^{18}\text{O}$ Snow Mass	-14°C	-4.8°C
Temp. Of Origin		
Cloud Top Temp	-19°C	-22°C
Snow CAE SO_4^{2-}	0.011 $\mu\text{g m}^{-3}$	0.072 $\mu\text{g m}^{-3}$
Cloud CAE SO_4^{2-}	1.1 $\mu\text{g m}^{-3}$	0.12 $\mu\text{g m}^{-3}$
Droplet Mean Dia.	8.3 mm	13.6 mm
Droplet Conc.	310 cm^{-3}	74 cm^{-3}
Cloud SCLW	0.13 g m^{-3}	0.14 g m^{-3}

on Feb. 15 and 19 were 0.02 mm hr^{-1} and 0.38 mm hr^{-1} , respectively.





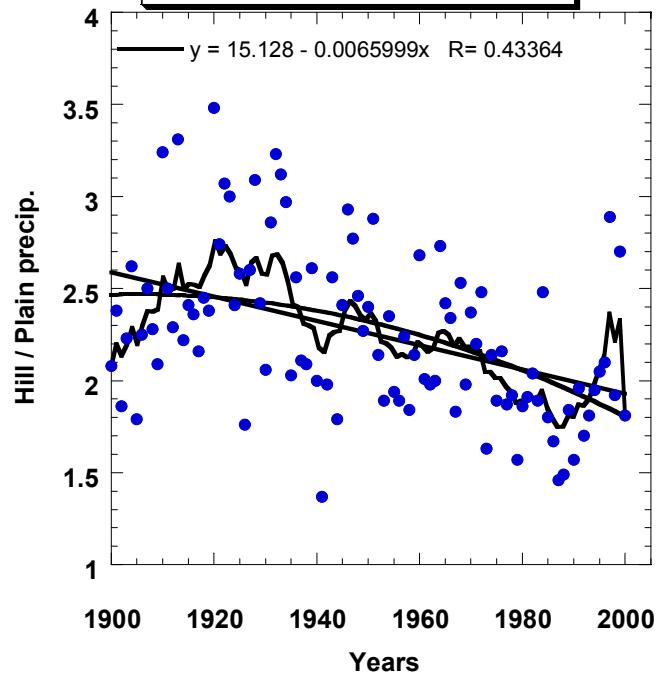
Concentration [ug/m³]Concentration [ug/m³]

Trends of fine and coarse aerosols as measured during winter (October-March) by the IMPROVE monitoring program. The increasing trend of fine aerosols along with decreasing trend of coarse aerosols in **Yosemite** causes clouds with more smaller droplets and increasingly suppressed precipitation even during the last 20 years. There is much less fine aerosols in **Lassen Volcano** at the northern Sierra that show no trend, implying no expected trend of suppressing precipitation. Coarse aerosols, if anything, enhance precipitation.

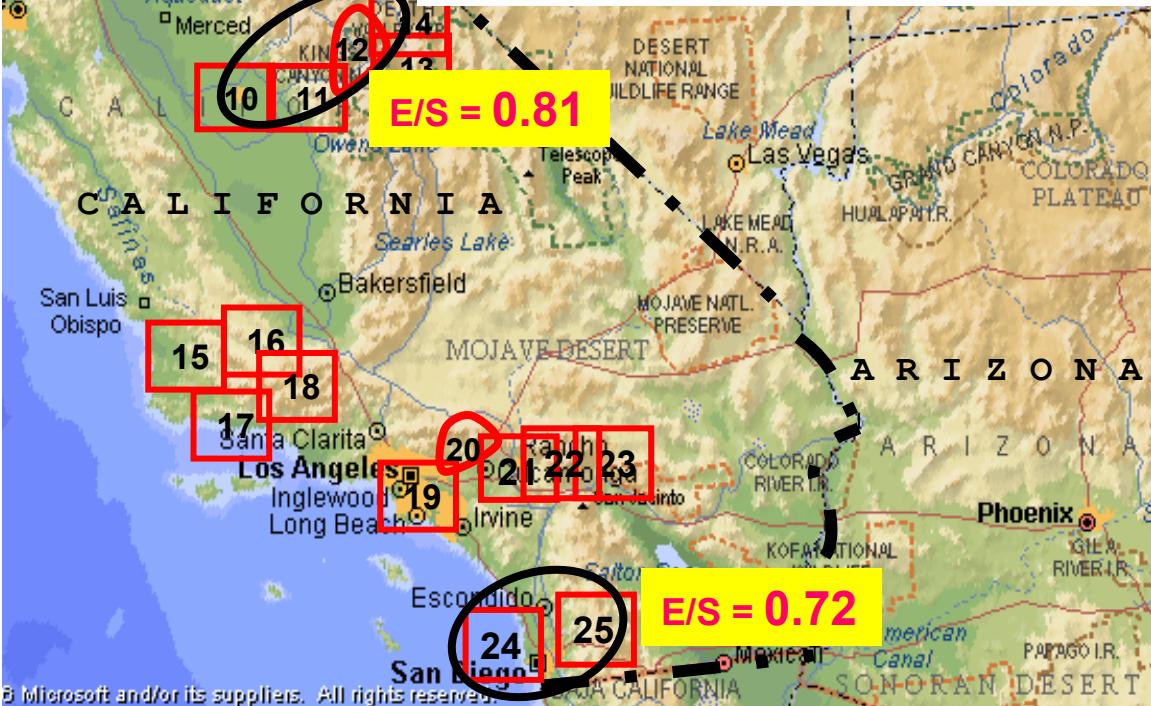
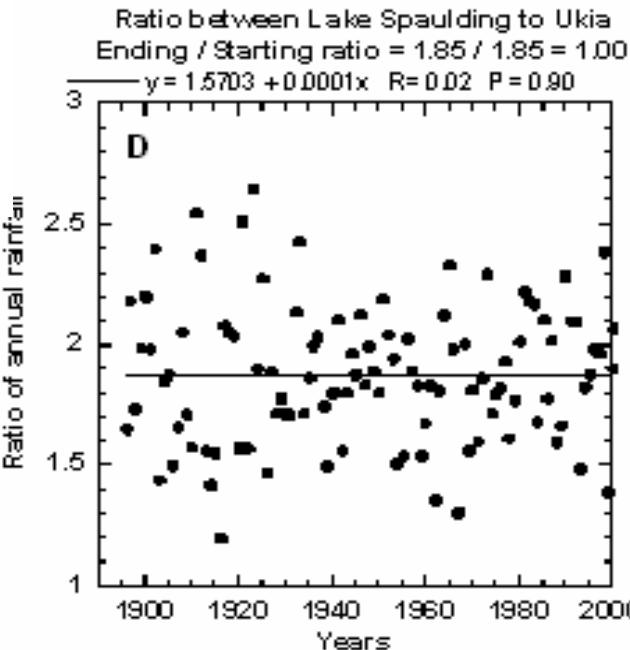
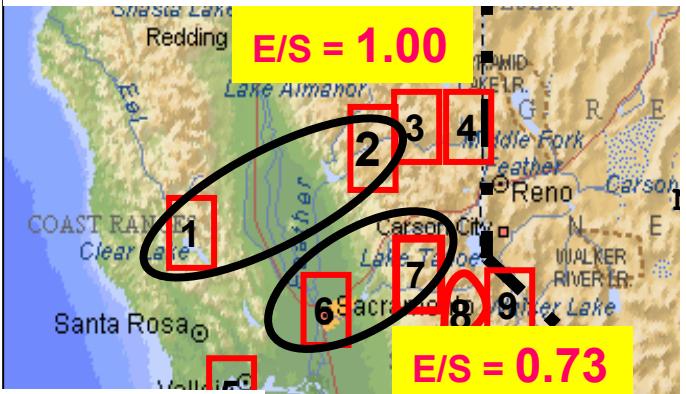
Legend

- 1E. Ukiah
- 2E. Lake Spaulding
- 3E. Bowman
- 4E. Boca
- 5A. San Francisco
- 6A. Sacramento
- 7A. Pacific House
- 8A. Cluster of snow packs in the divide line downwind to Sacramento
- 9A. Woodfords
- 10B. Fresno
- 11B. Grant Grove

—●— Ro_Placerville_Sacramento
Ending / Starting = $1.90/2.62=0.73$



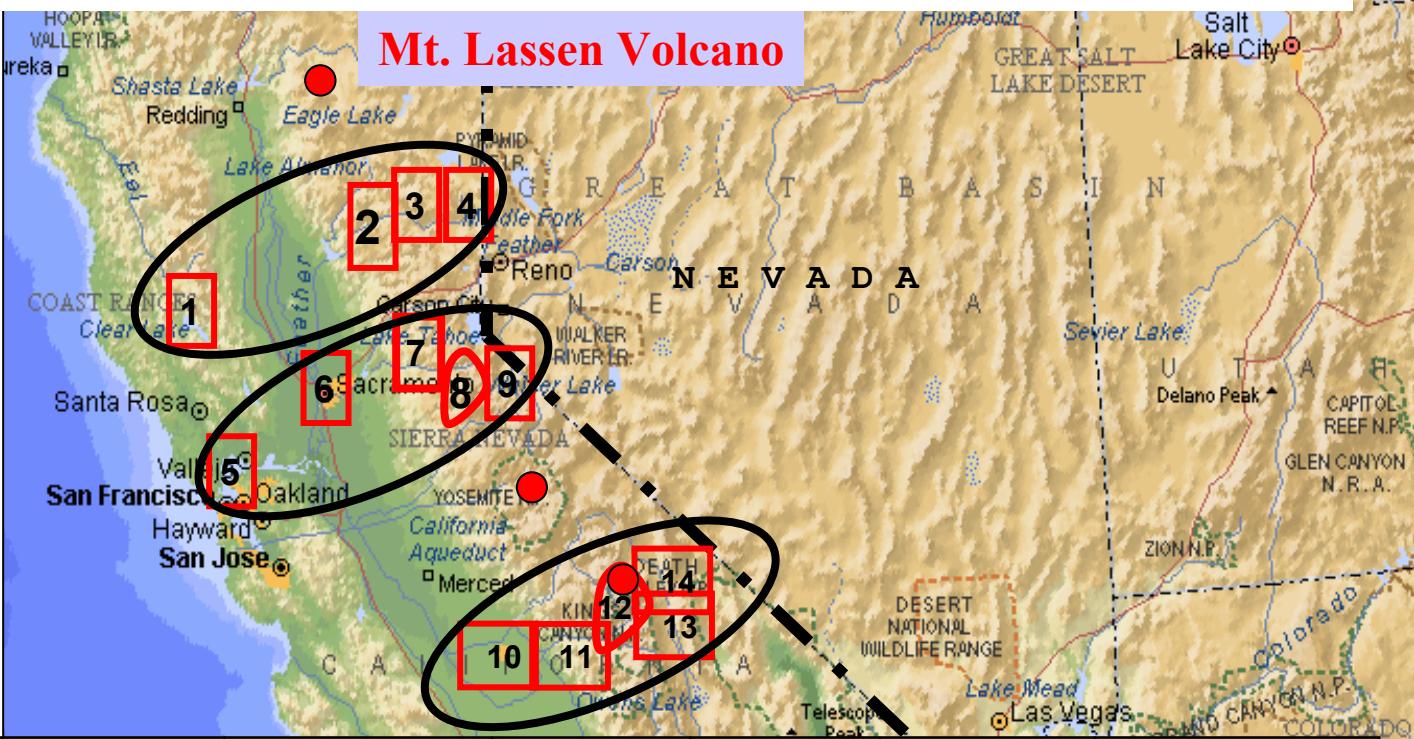
Trends of orographic precipitation enhancement factors



Legend

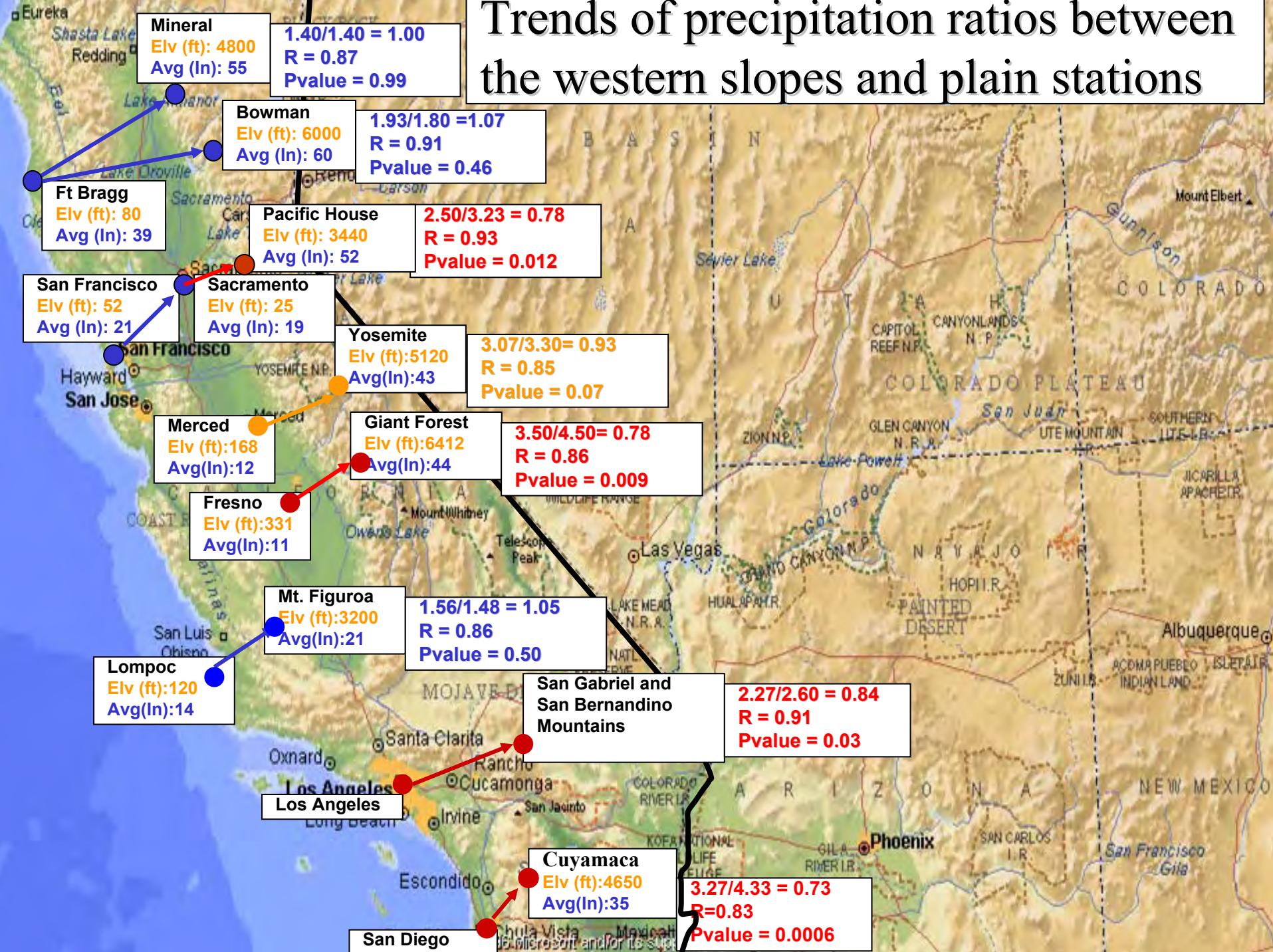
- 1E. Ukiah
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 7A. Pacific House
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 9A. Woodfords
 10B. Fresno
 11B. Grant Grove
 12B. Cluster of snow packs in the divide line downwind to Fresno
 13B. Glacier
 14B. Bishop Lake
 15F. Lompoc
 16F. Mt. Figuroa
 17F. S.
 18F. M.
 19C. I.
 20C. O.
 downn
 21C. I.
 22C. I.
 23C. I.
 24. Sa
 25. Cu
- | Station | Elev.(m) | Period | Mean
$\mu\text{eq l}^{-1}$ | 2001-
2002 | Trend
$\mu\text{eq l}\cdot\text{y}^{-1}$ | Precip. Ro
change % |
|-------------------------|----------|-----------|-------------------------------|---------------|---|------------------------|
| Sequoia/
Fresno | 1902 | 1981-2002 | 41.3 | 35.4 | +0.31 | -24 (1945-
2000) |
| Yosemite/
Sacramento | 1408 | 1982-2002 | 30.7 | 36.5 | -0.06 | -22 (1945-
2000) |
| Lassen/
Ukiah | 1765 | 2001-2002 | --- | 17.7 | --- | 0 (1945-
2000) |

Ionic content of precipitation, by the National Atmospheric Deposition Program



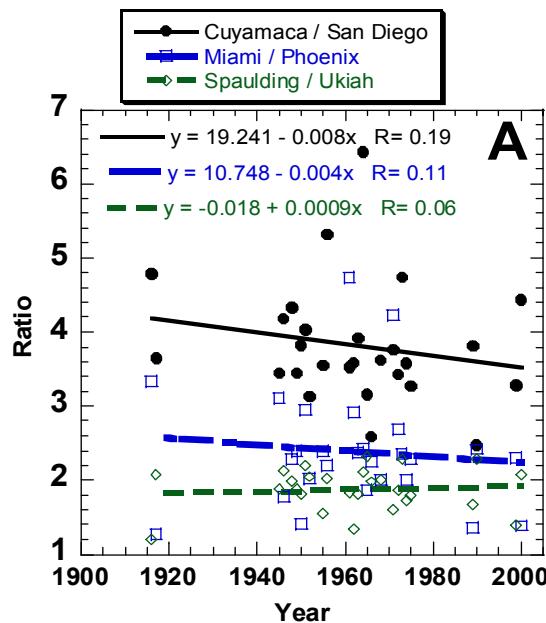
Station	Elev.(m)	Period	Mean $\mu\text{eq l}^{-1}$	2001- 2002	Trend $\mu\text{eq l}\cdot\text{y}^{-1}$	Precip. Ro change %
Sequoia/ Fresno	1902	1981-2002	41.3	35.4	+0.31	-24 (1945- 2000)
Yosemite/ Sacramento	1408	1982-2002	30.7	36.5	-0.06	-22 (1945- 2000)
Lassen/ Ukiah	1765	2001-2002	---	17.7	---	0 (1945- 2000)

Trends of precipitation ratios between the western slopes and plain stations

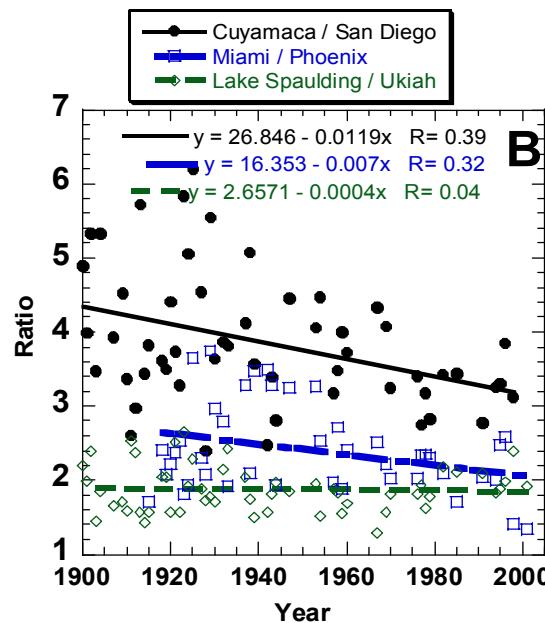


Testing alternative explanations

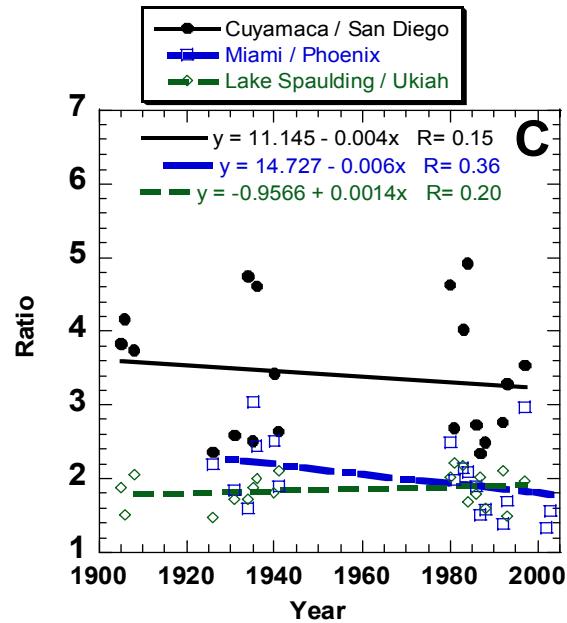
PDO < -0.5



-0.5 < PDO < 0.5



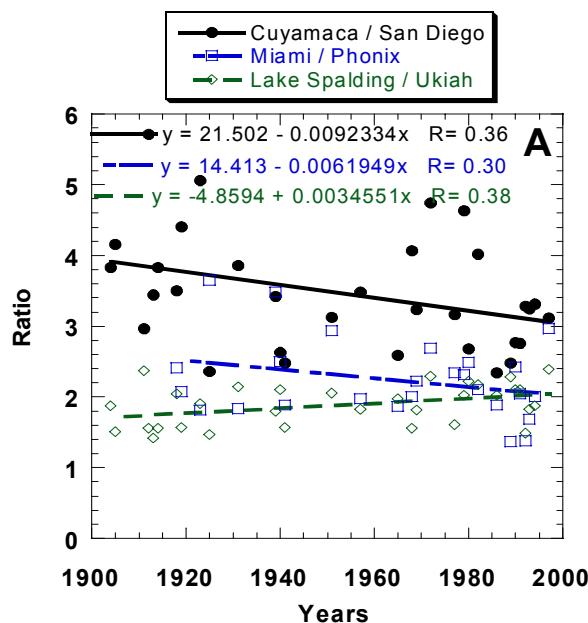
PDO > 0.5



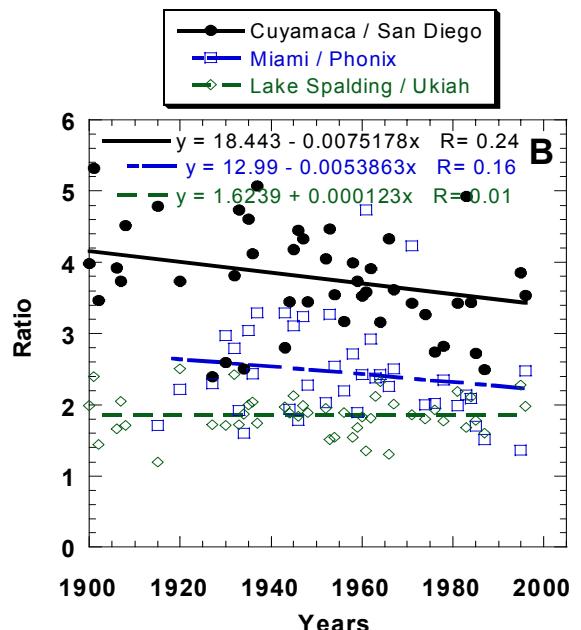
Pacific Decadal Oscillations (PDO) can affect the rainfall amounts and orographic enhancement factor. PDO classification to three states and the ratio of hilly / plain pairs of rain gauges in **polluted** areas (**Cuyamaca / San Diego**, **Miami / Phoenix**) and relatively **pristine** area (**Lake Spaulding / Ukiah**). The ratio for the two polluted pairs decreases in all PDO states, while no trend is indicated for the ratio at the relatively pristine area. Therefore, **trends in PDO cannot explain the decreasing trends of orographic precipitation relative to the lowland areas**. The same analyses for all other gauge pairs gave similar results.

Testing alternative explanations

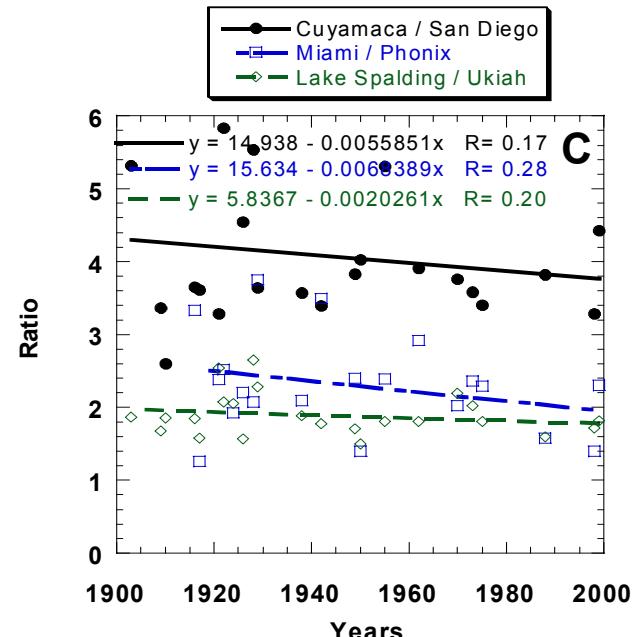
SOI < -0.5



-0.5 < SOI < 0.5

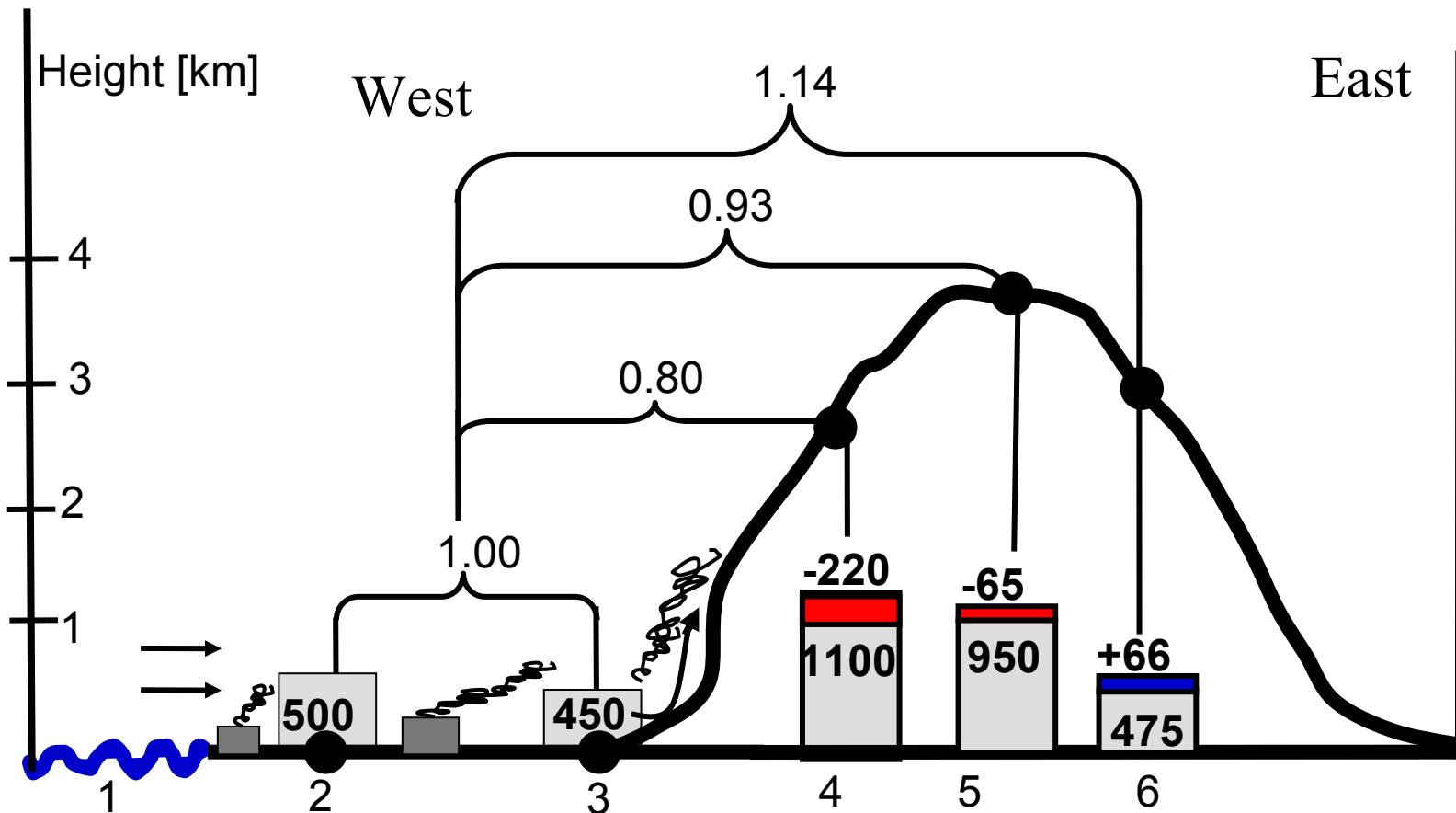


SOI > 0.5



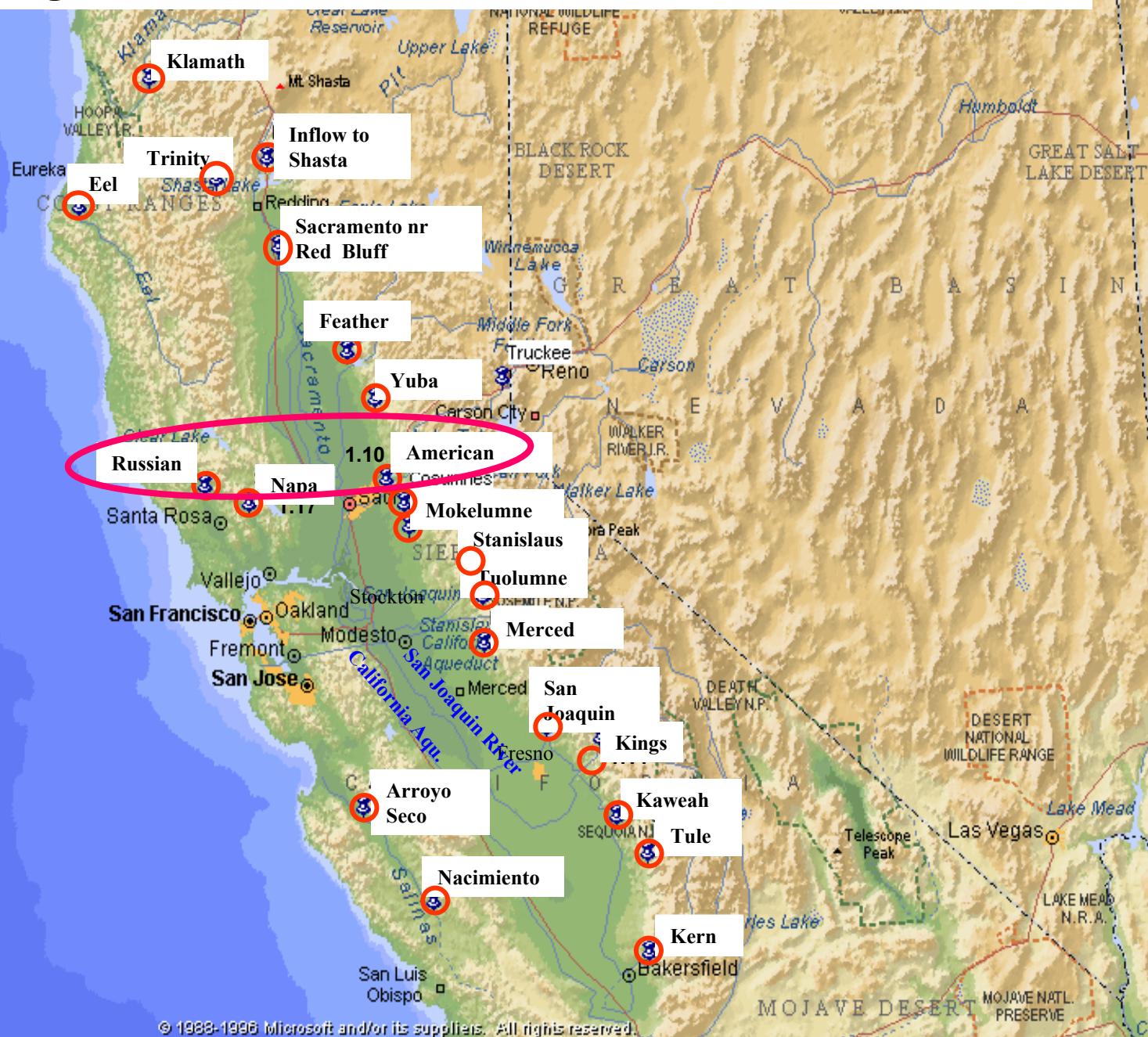
Also Southern Oscillations Index (SOI) can affect the rainfall amounts and orographic enhancement factor. SOI classification to three states and the ratio of hilly / plain pairs of rain gauges in **polluted areas (Cuyamaca / San Diego, Miami / Phoenix)** and relatively **pristine area (Lake Spalding / Ukiah)**. The ratio for the two polluted pairs decreases in all SOI states, while no trend is indicated for the ratio at the relatively pristine area. Therefore, **trends in both SOI and PDO cannot explain the decreasing trends of orographic precipitation relative to the lowland areas**. The same analyses for all other gauge pairs gave similar results.

Topographic cross section showing the effects of urban air pollution on precipitation as the clouds moves from west to east across the mountains



Givati and Rosenfeld (JAM, 2005)

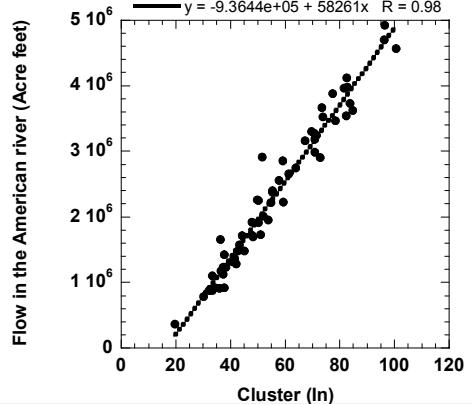
Sites of long term undisturbed river flow measurements



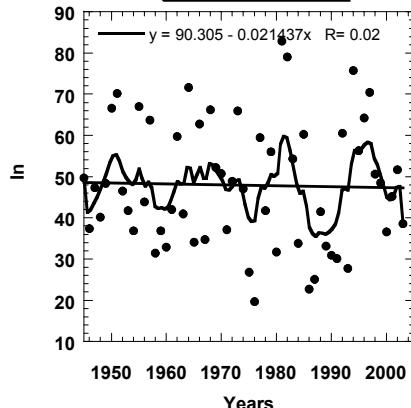
Sierra Nevada

American River

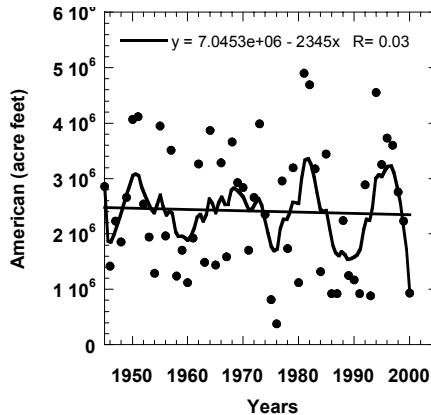
Correlations



Rain gauges

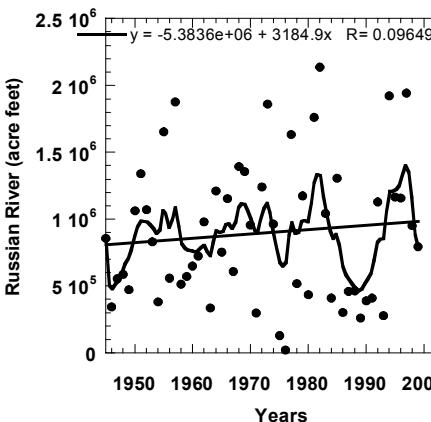
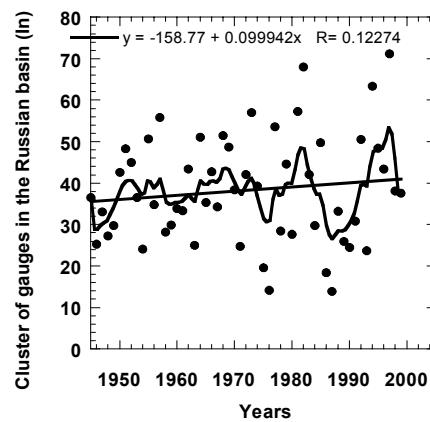
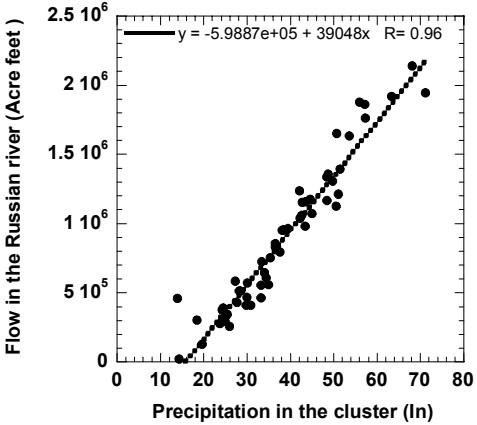


River flows

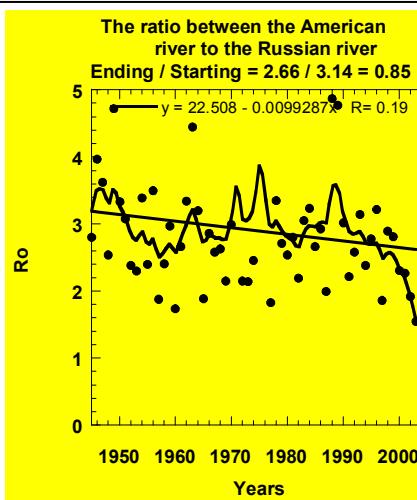
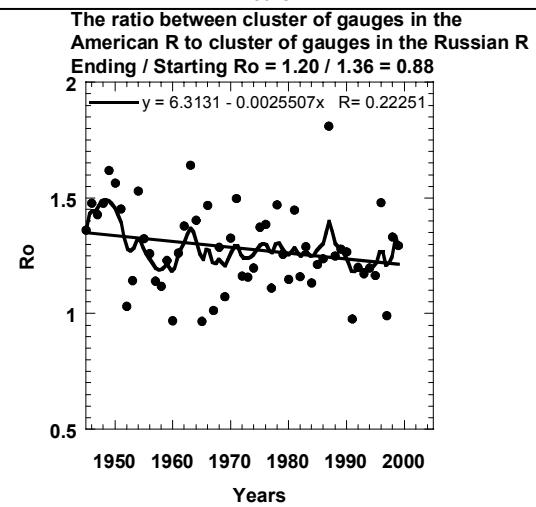
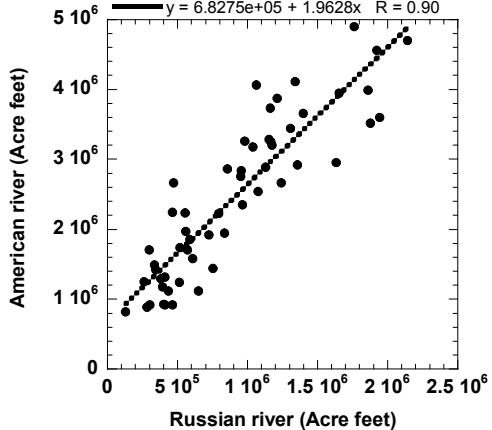


Coastal Range

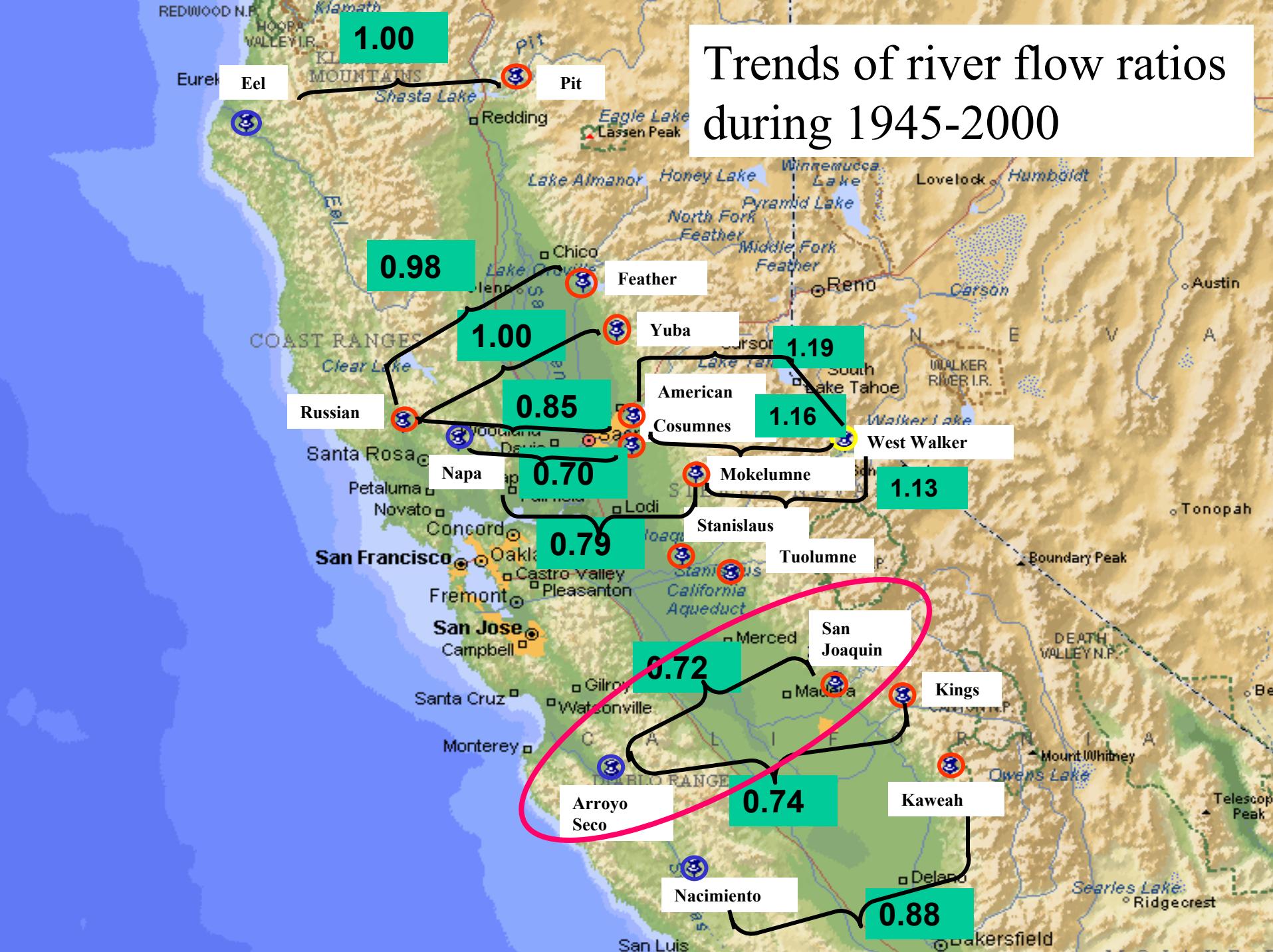
Russian River



Sierra / Coastal relations



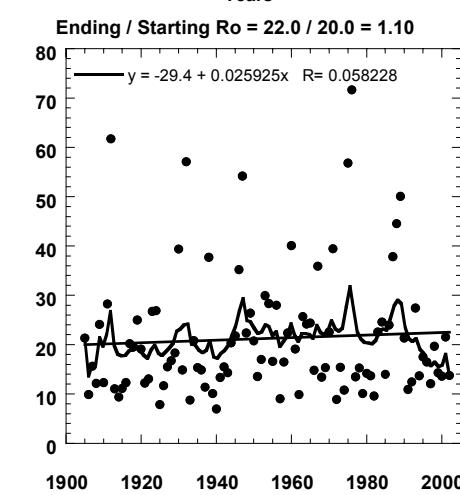
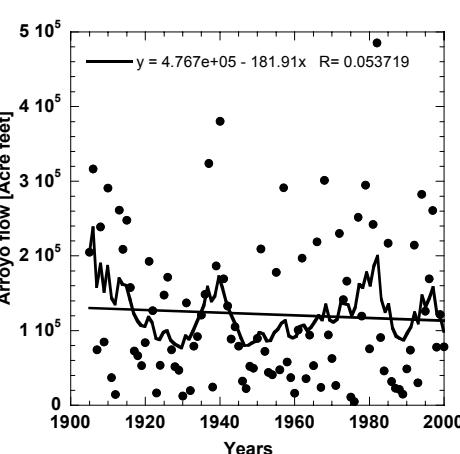
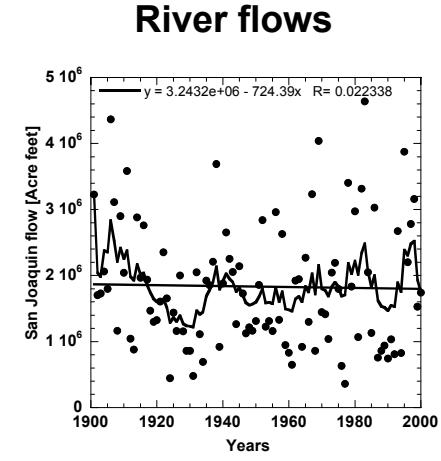
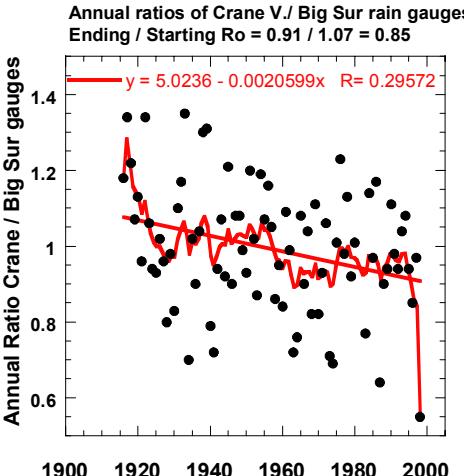
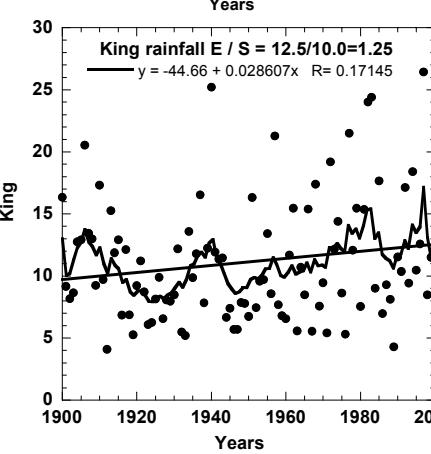
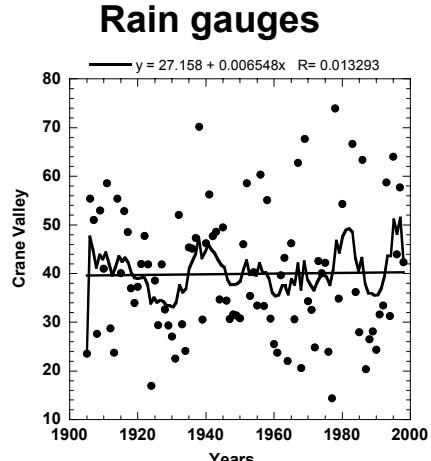
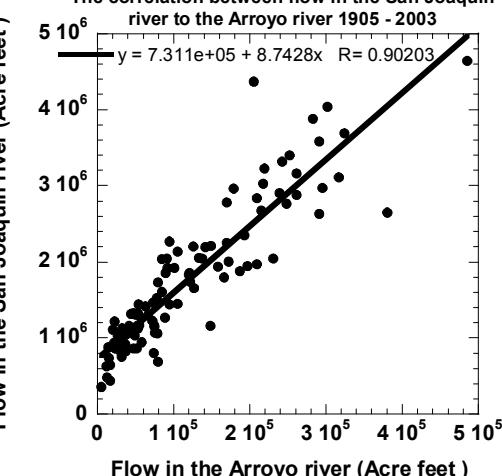
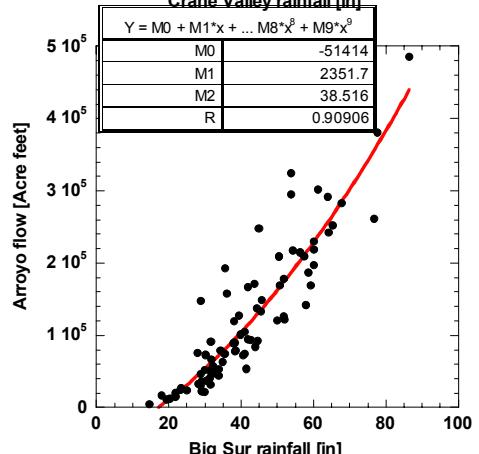
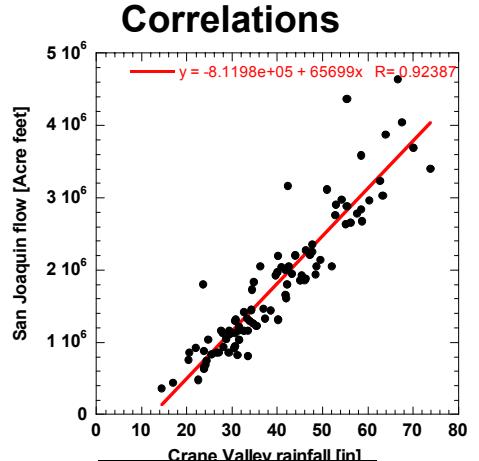
Trends of river flow ratios during 1945-2000



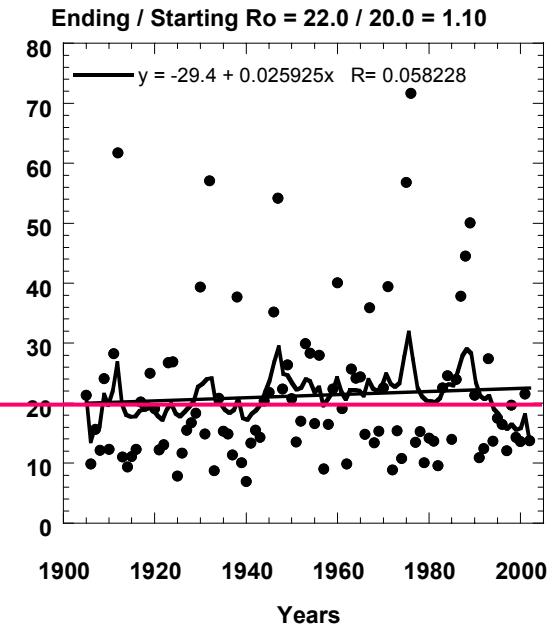
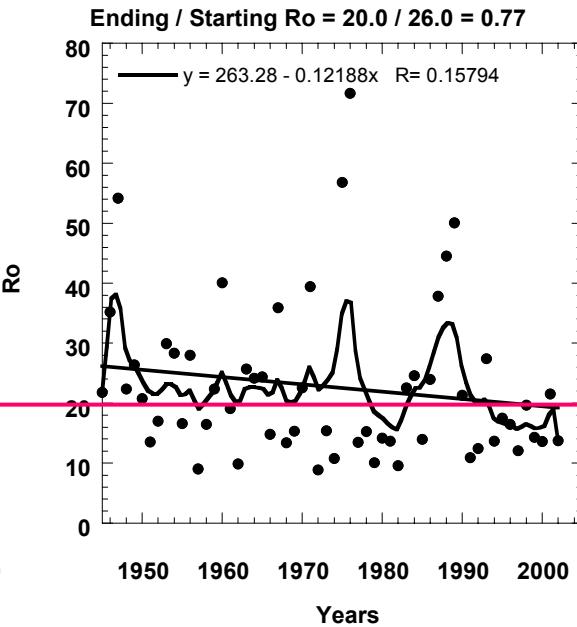
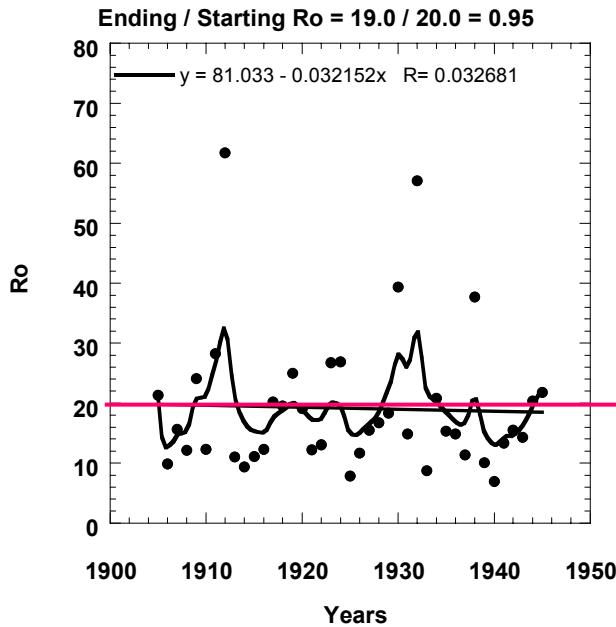
Sierra Nevada

Arroyo River

Sierra / Coastal relations



The correlation and ratio between flow in the San Joaquin river to the Arroyo river 1905 - 2003



1905 - 2045

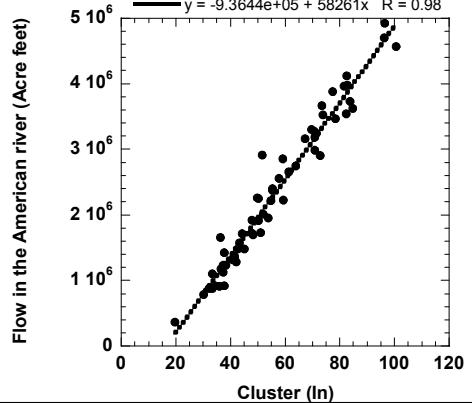
1945 - 2003

1905 - 2003

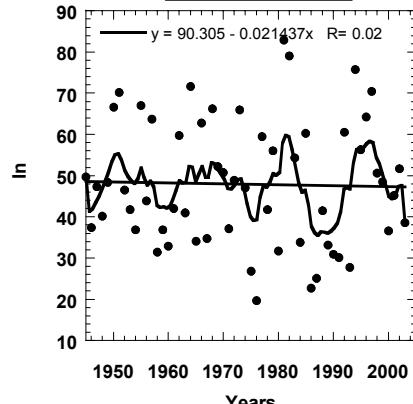
Sierra Nevada

American River

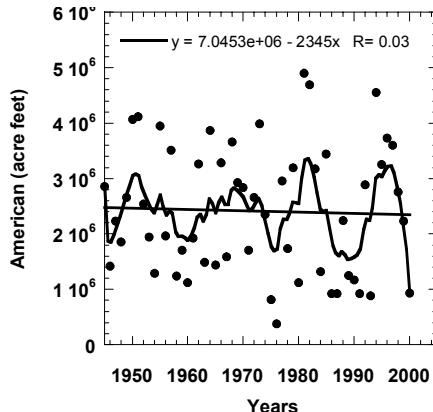
Correlations



Rain gauges

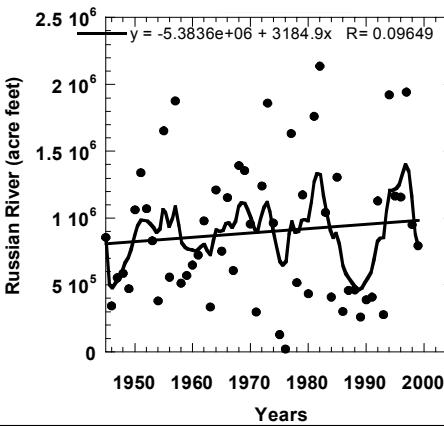
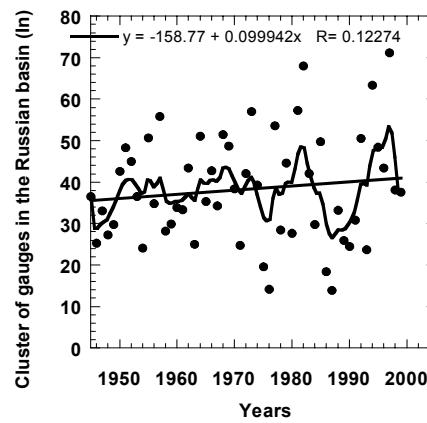
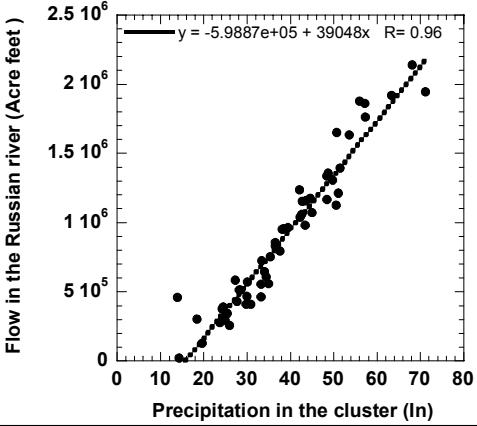


River flows

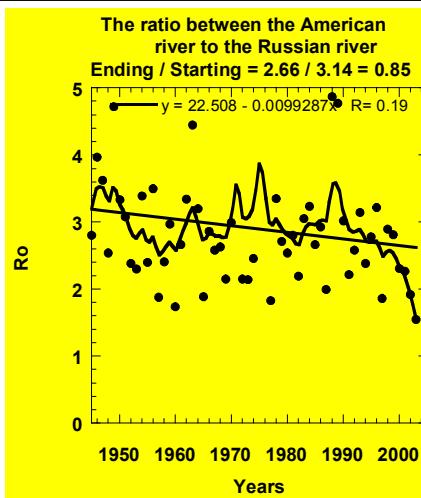
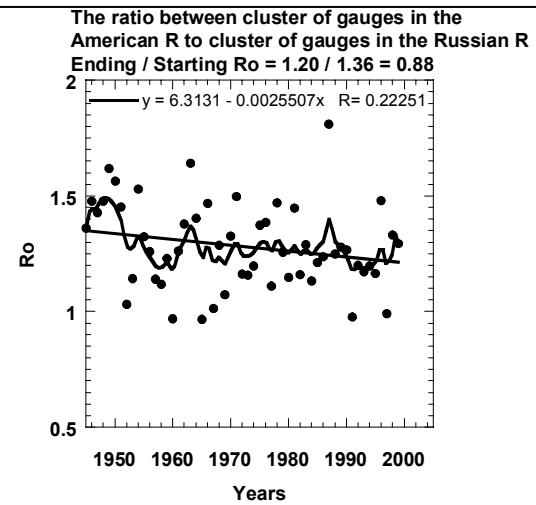
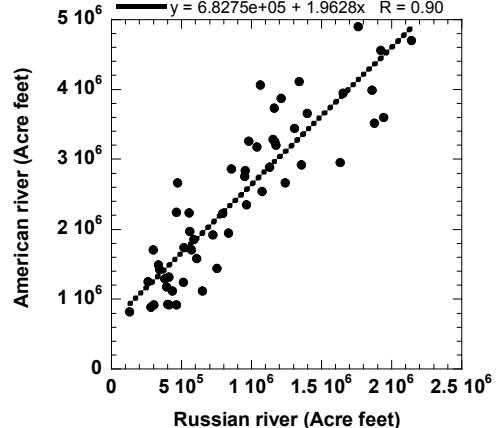


Coastal Range

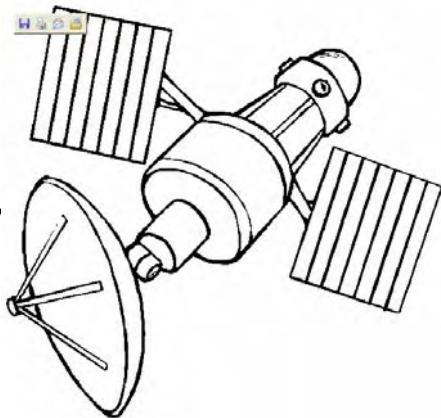
Russian River



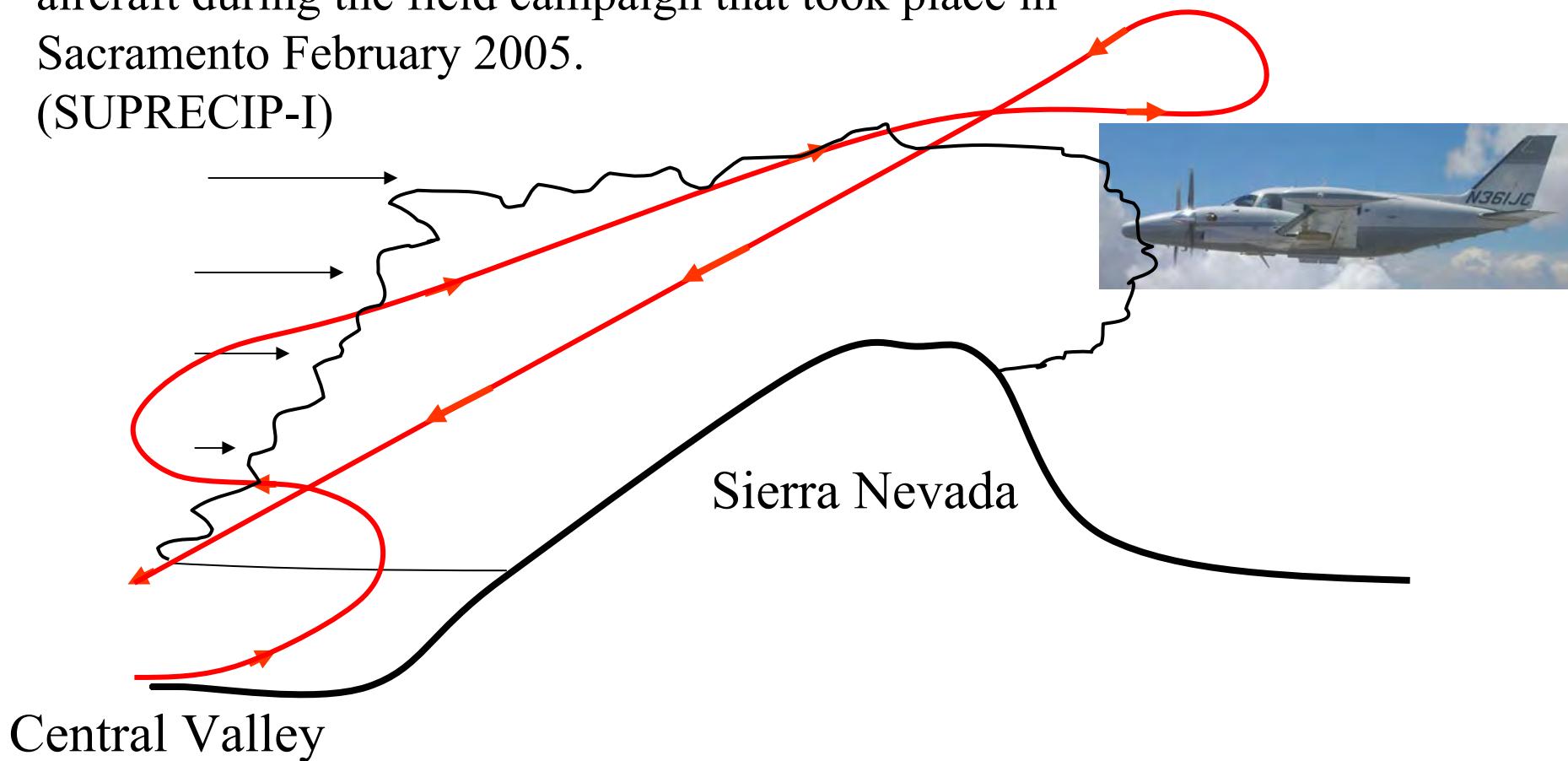
Sierra / Coastal relations

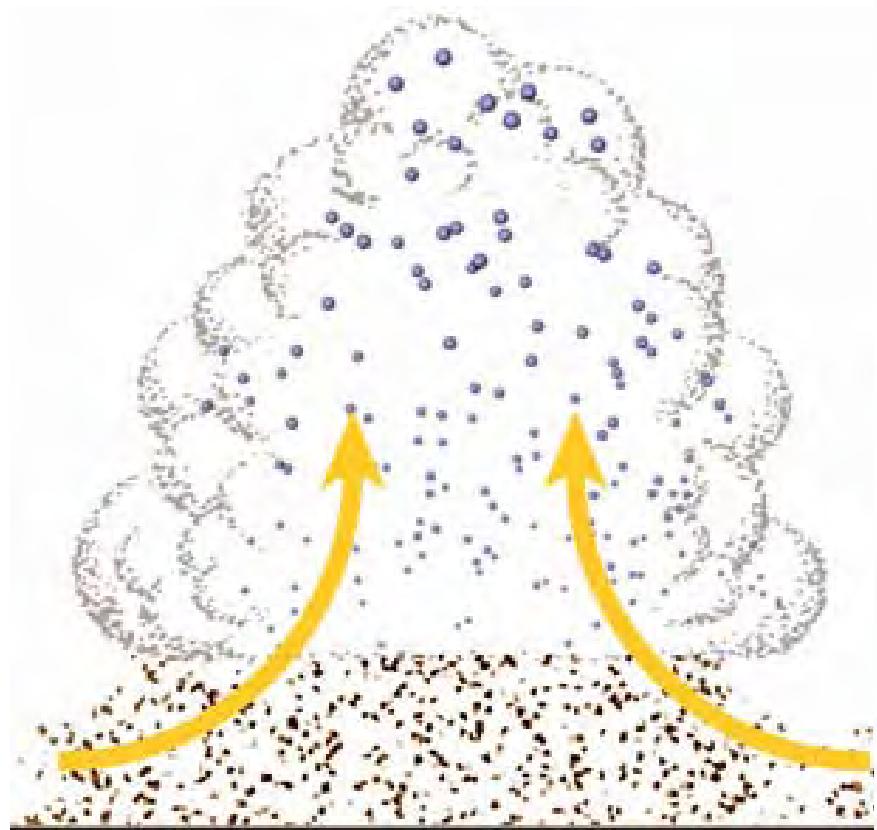
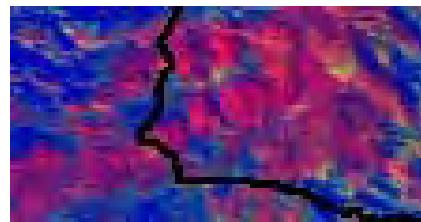
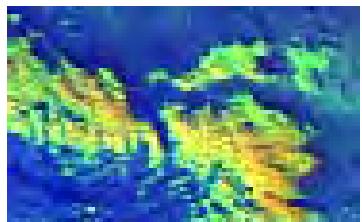


Cloud microstructure, precipitation processes and the way they are affected by pollution aerosols were measured by means of remote sensing from satellites and radars, and by in-cloud instrumented airplanes.

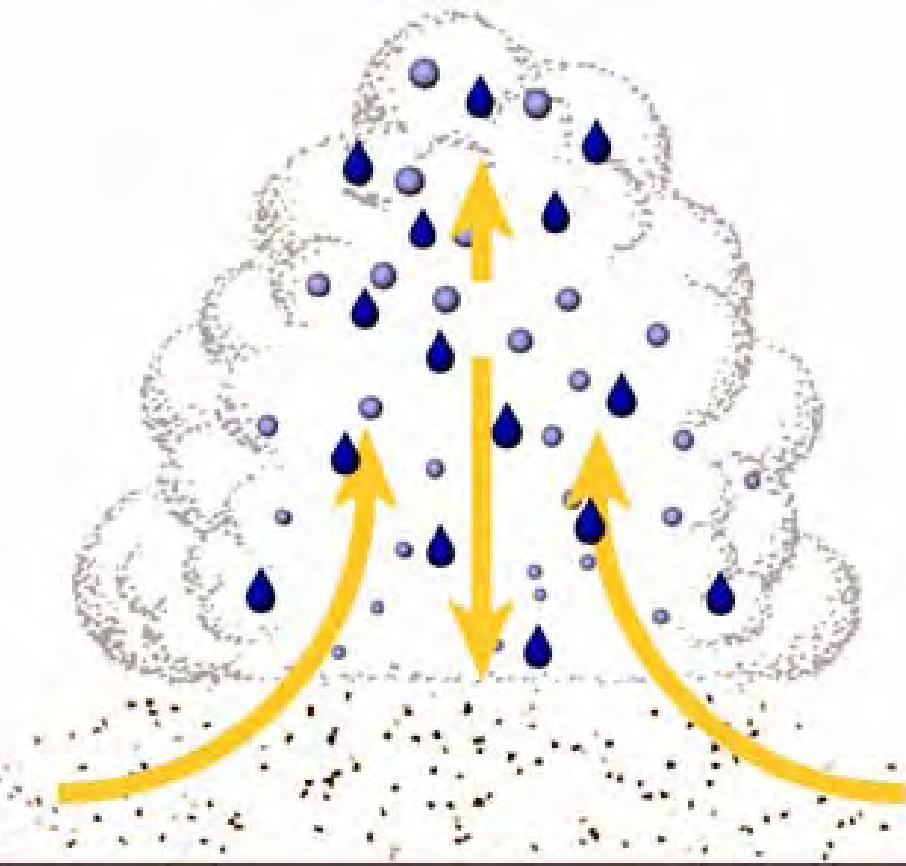


Below is the flight plan strategy of the cloud physics aircraft during the field campaign that took place in Sacramento February 2005.
(SUPRECIP-I)

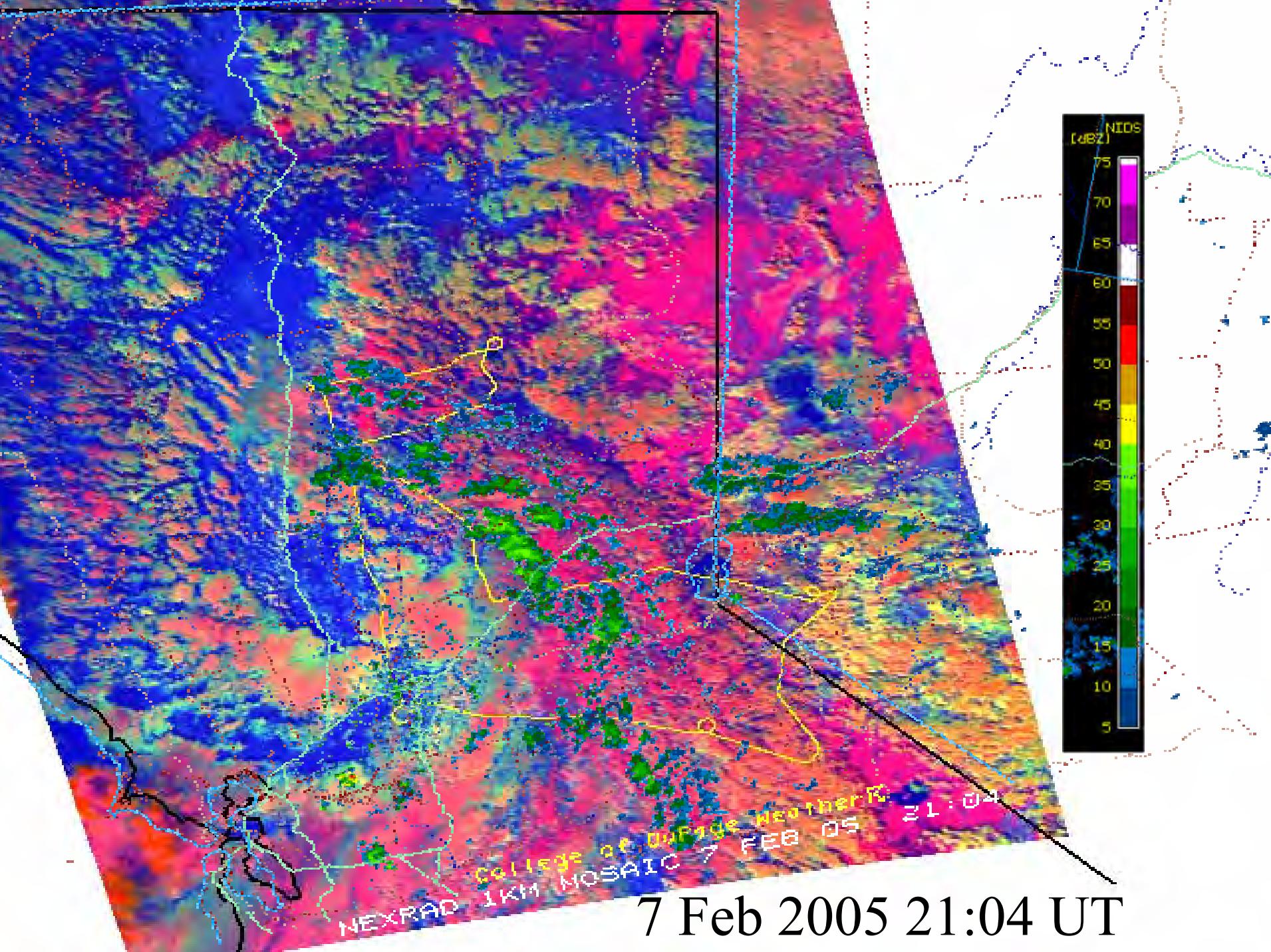


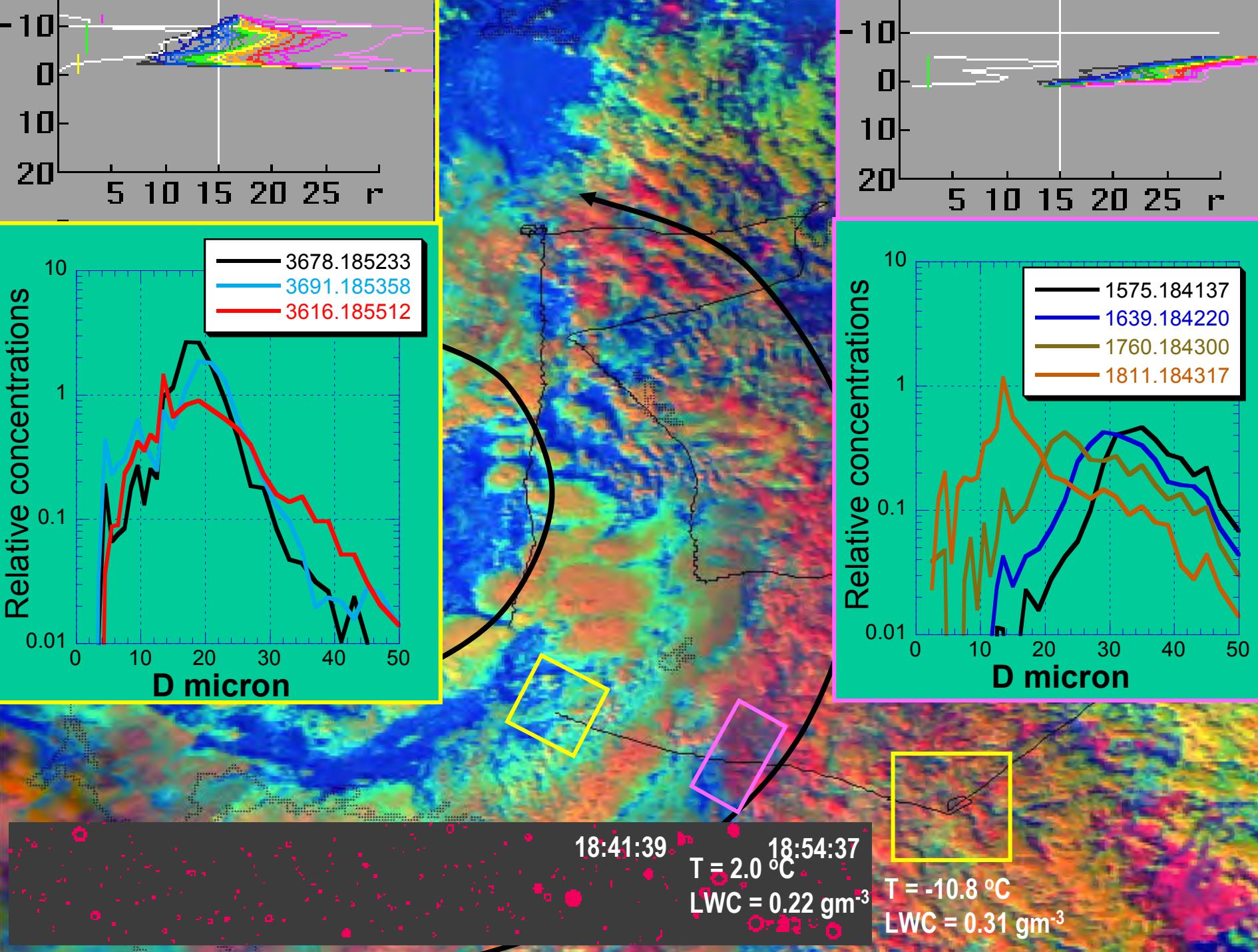


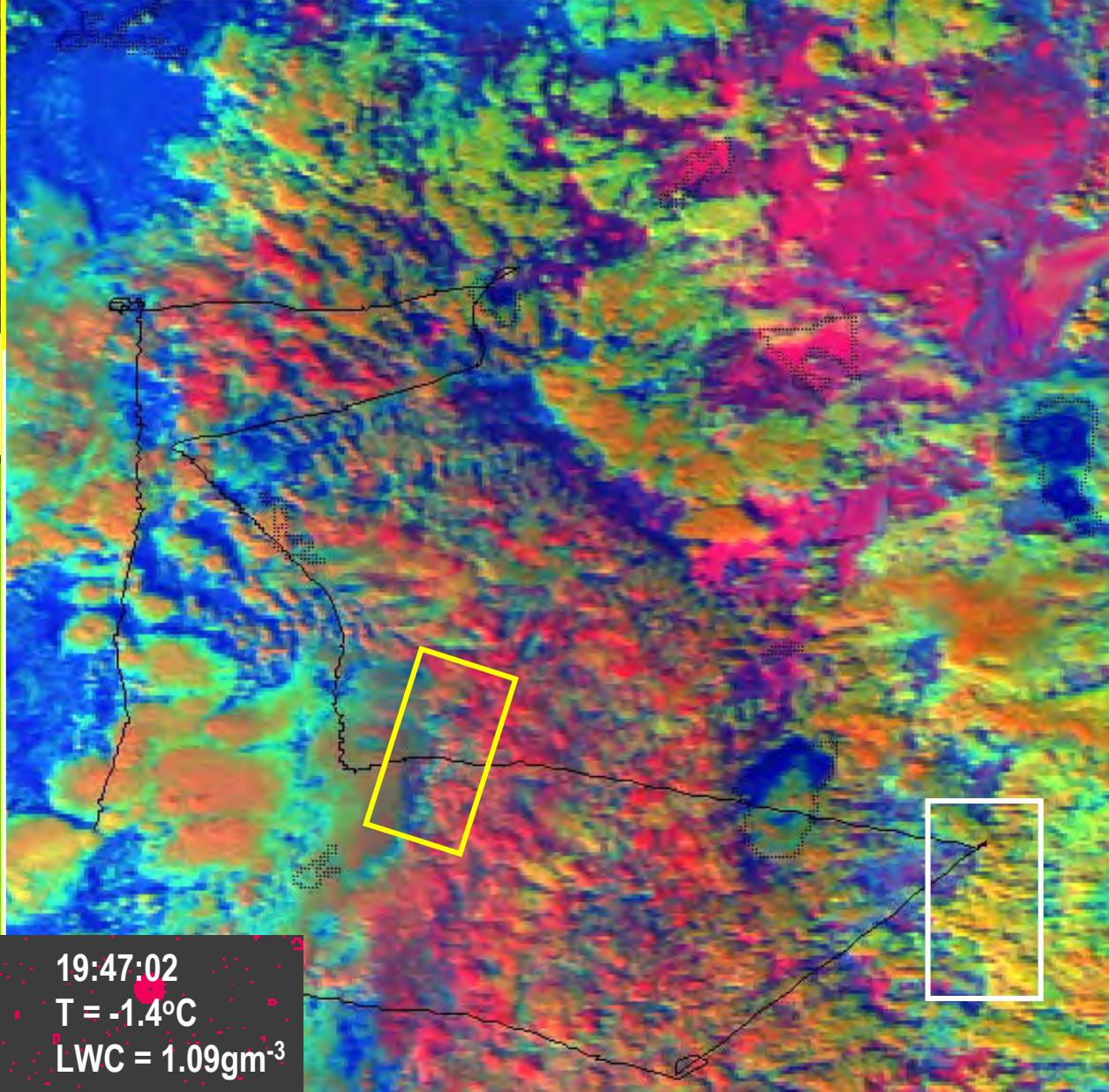
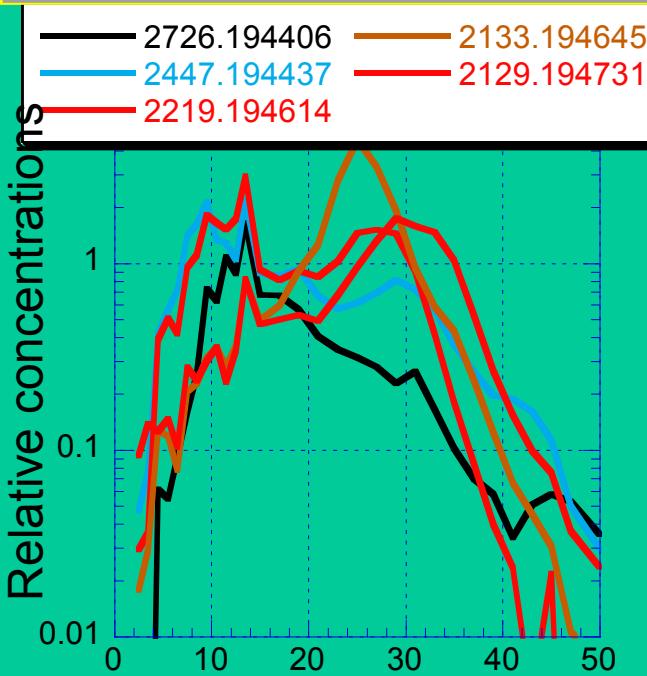
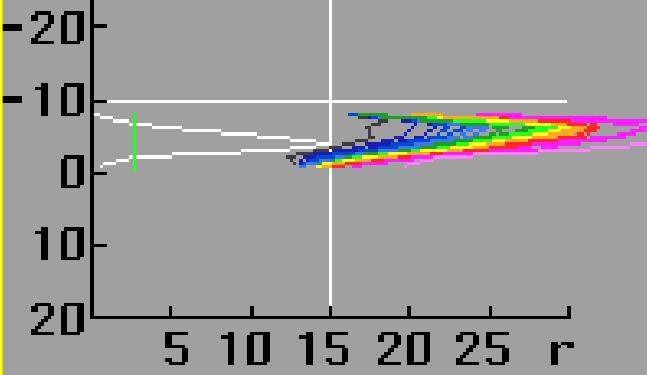
Polluted

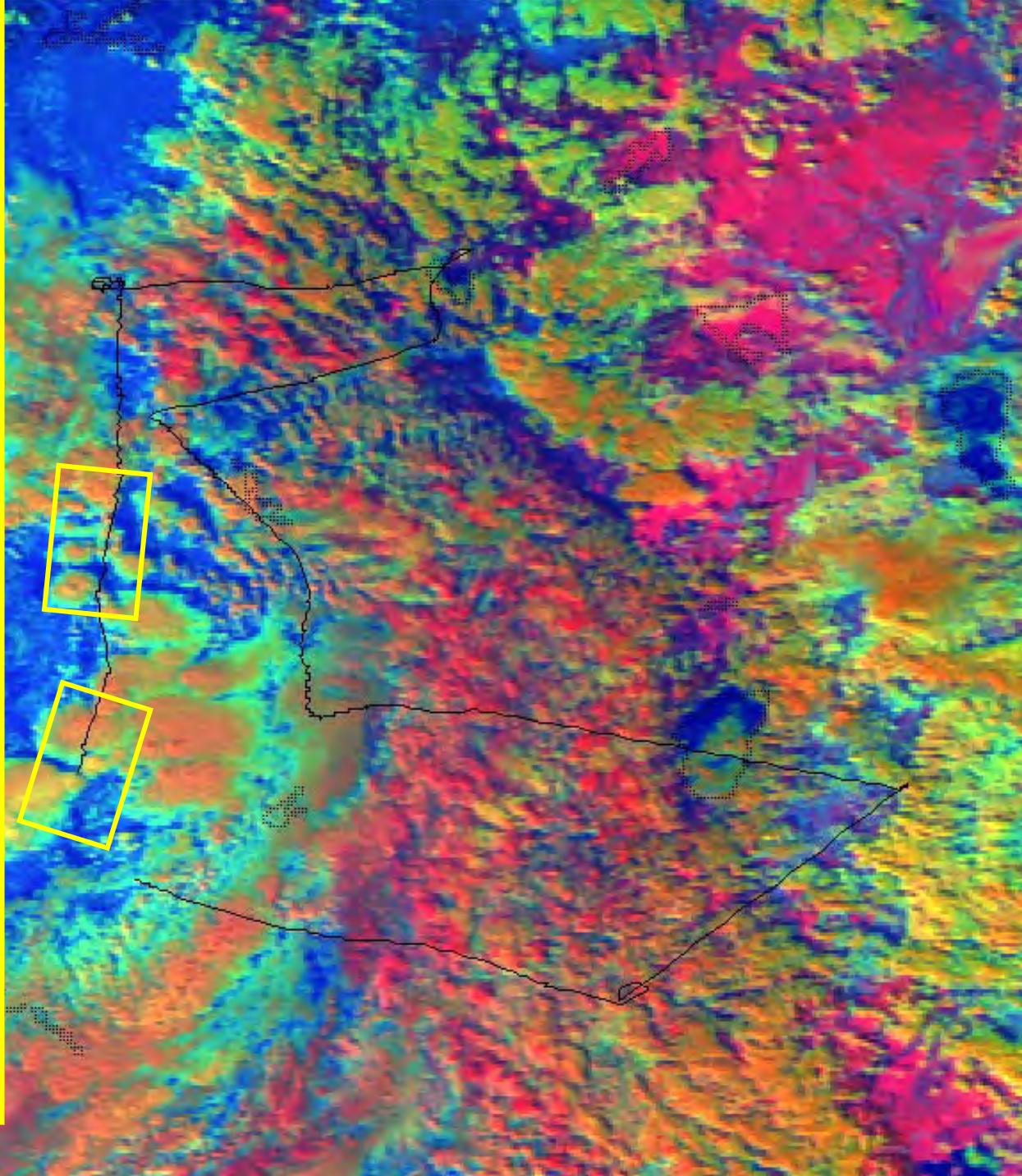
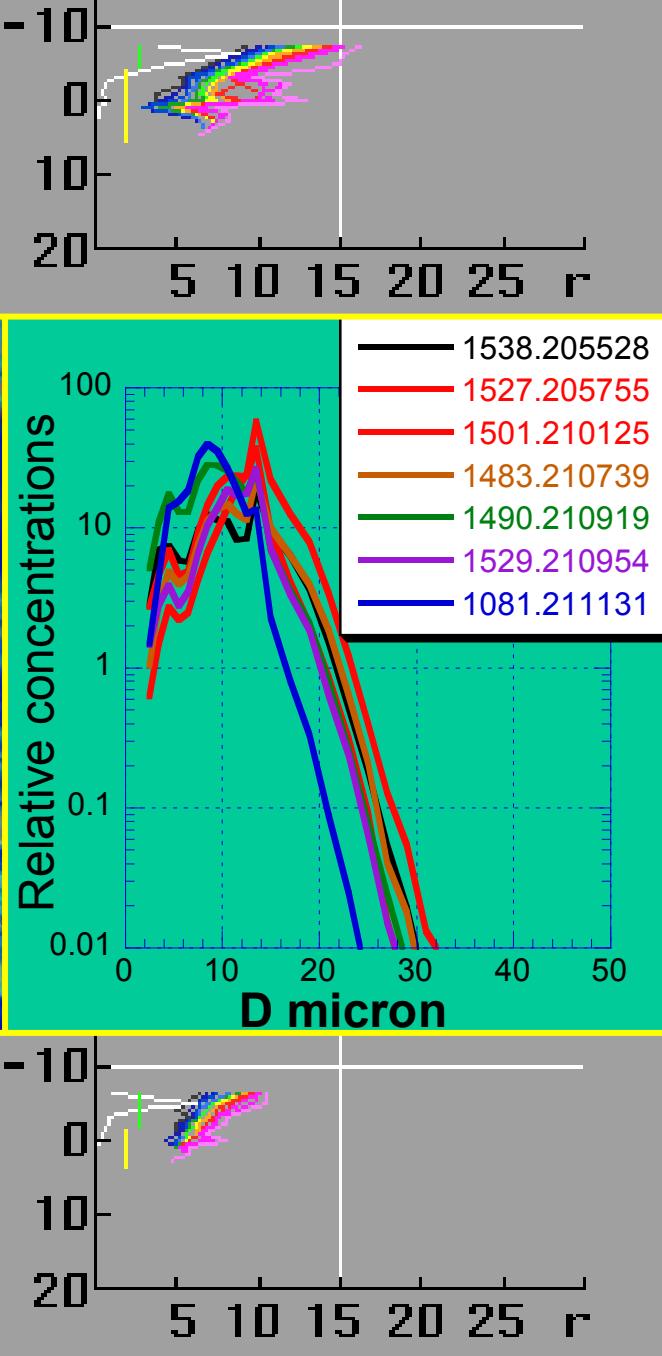


Pristine





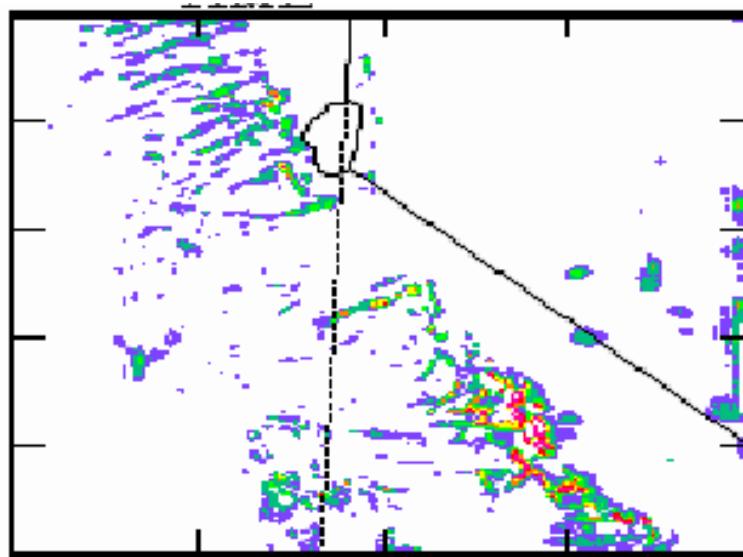




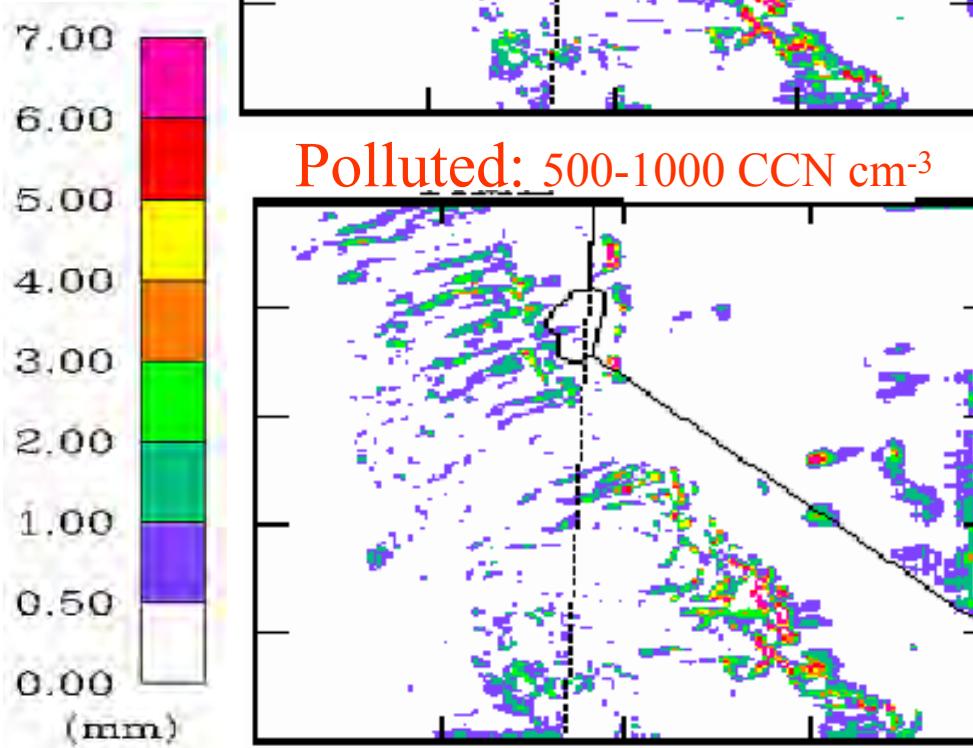
Models with spectral (bin) microphysics

Scientific group of the HUJI *is developing a numerical basis consisting of a complex of novel one-, two-, and three-dimensional cloud microphysical models for simulation of effects of AEROSOLS on PRECIPITATION and effects of CLOUDS ON AEROSOLS*

Clean: 50-100 CCN cm^{-3}



Polluted: 500-1000 CCN cm^{-3}

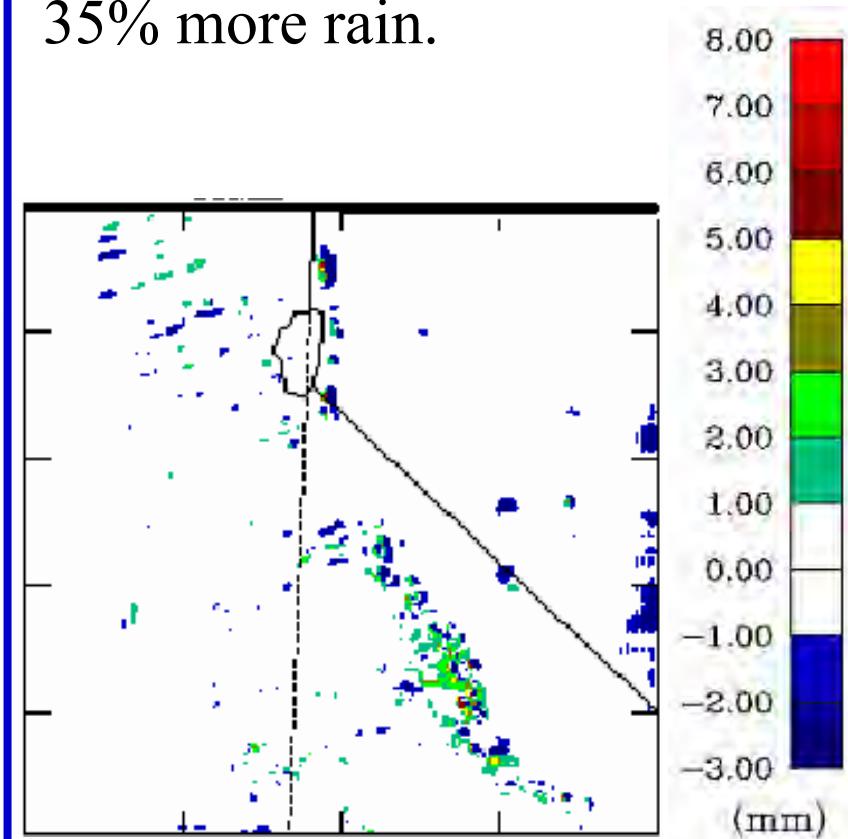


Rain intensities [mm hr^{-1}]

3-D 1-km MM5 simulation for rainfall accumulation during 12 hours starting at 7 Dec 2003 15:00 UT.

Sensitivity to aerosols concentrations.

The clean case produce 30%-35% more rain.



Clean - Polluted [mm hr^{-1}]

Conclusions (1):

Precipitation records suggest that particulate air pollution suppresses orographic precipitation and river flows. This is supported by:

1. Aerosol measurements showing recent increases in rural fine aerosols with decrease of coarse aerosols. Chemical analyses of rainwater composition is consistent with the aerosol measurements.
2. Satellite observations show air pollution reducing cloud droplet sizes in California.
3. Radar measurements show suppressed precipitation in the satellite inferred polluted clouds in California.
4. Aircraft measurements validated the remote sensing inferences.
5. Mountain-top in-cloud measurements showed that pollution aerosols decrease the riming of ice crystals and hence decrease the snowfall rate at the Colorado Rockies (DRI).

Conclusions (2):

6. Cloud modeling reproduced the sensitivity of orographic precipitation to pollution.
7. Several alternative meteorological explanations for the indicated decreases in orographic precipitation were negated, including the Pacific Decadal Oscillations, El Niño, and some other variables.
8. The tight linear relation between precipitation and river runoff in the Sierra Nevada means that the loss of rainfall there is likely associated with similar percentage of loss of river flow of ~15%.

Future plans:

Until now we have just documented the occurrence of the potential problem and its possible causes. Now we have to quantify it by additional measurements and simulations.

Please see additional information poster #18